

The wind tunnel (Type: XNJD-1) of Southwest Jiaotong University, a closed circuit wind tunnel with two tandem closed test sections, was used to carry out the investigation. The section model was tested in the second test section, and the dimension of the test section is 2.4m×2.0m ($W \times H$). The simply supported aeroelastic model was tested in the first test section, and the dimension of this section is 3.6m×3.0m ($W \times H$).

The VIV tests were conducted by free vibrating method in smooth flow. The vibration amplitude was recorded by laser displacement meters and the lock-in area was found, the acquisition of pressure data were preceded in the three stages (before the VIV region, in the VIV region and after the VIV region). In the VIV region, pressure data were acquired at different amplitudes which depend on three different damping levels, and the effects of VIV amplitude on the correlation of vortex-induced force were studied in detail. In addition, the pressure distribution characteristics of different cross sections were analyzed in detail, especially the points near the wake. This paper only pays attention to the correlation of the model in different amplitude.

3. SPANWISE CORRELATION ANALYSIS

The correlation of trapezoidal section model is affected at a large extent by the change of attack angle. The correlation coefficient will increase with the increase of amplitude at 0° attack angle (Fig. 3).The change of attack angle of oncoming flow will affect the aerodynamic characteristics of section. With the increase of attack angle the points with weak correlation at the wake will reduce the correlation (Fig. 4).

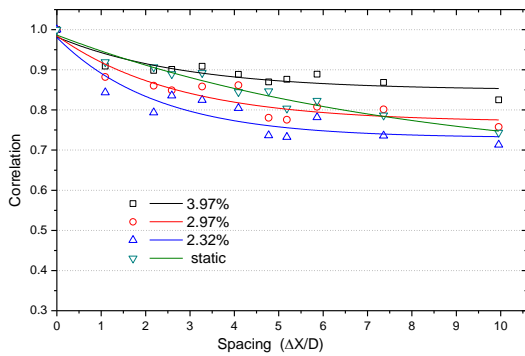


Fig. 3 The correlation coefficients of section model at different amplitudes

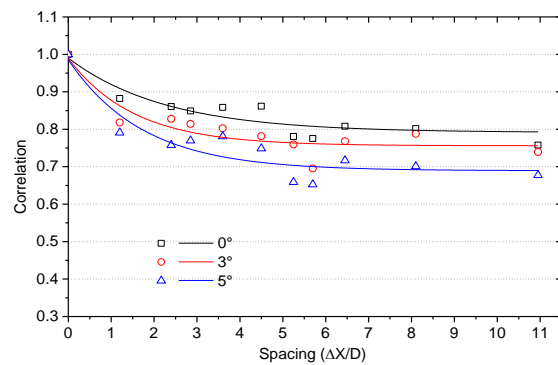


Fig. 4 The correlation of section model at different attack angles

The correlation of vortex-induced force act on square cylinders along the span was studied in detail by Wilkinson (1981). Also, he found the correlation of vortex-induced force varied with vibration amplitude, a double exponential correlation semi-empirical formula (Eq. 1) was fitted by Ehsan and Scanlan (1990) based on Wilkinson's test results.

$$R(\Delta x) = \exp[-f_1(\eta) \left(\frac{\Delta x}{D}\right)^{f_2(\eta)}] \quad (1)$$

in which, η is the ratio between vibration amplitude and cross wind size D ; $\Delta x/D$ is spanwise spacing; and f_1 and f_2 were fitted as following form:

$$f_1(\eta) = \frac{0.052}{0.298 + \eta^{0.25}}, \quad f_2(\eta) = \frac{0.065}{0.042 + \eta} \quad (2)$$

For the test results of trapezoidal section model mentioned in this paper, the two functions f_1 and f_2 can be fitted as Eq. 3, and the correlation coefficients of the test and fitted results can be seen in Fig. 5.

$$\left. \begin{aligned} f_1(\eta) &= \frac{-0.1038}{-4.3259 + \eta^{-0.3441}} \\ f_2(\eta) &= \frac{0.1798}{0.4734 + \eta} \end{aligned} \right\} \quad (3)$$

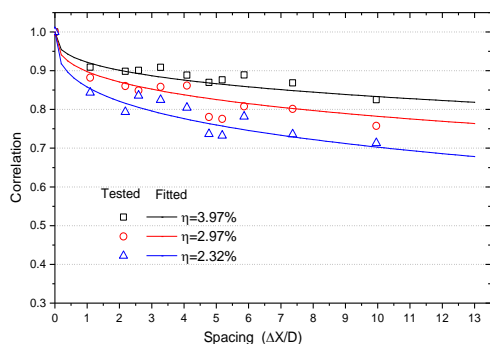


Fig.5 The correlation function fitted by section model test result

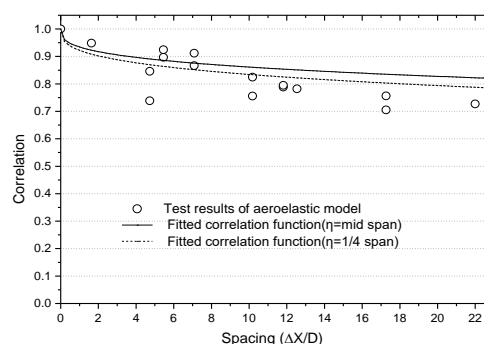


Fig.6 The comparison between test results of aeroelastic model and fitted correlation function by section model

The correlation coefficients of simply supported aeroelastic model were shown in Fig. 6. The test results of aeroelastic model are closed to the correlation function fitted by section model when the span spacing is relatively small, and the difference increase with the spacing grows. Although the correlation function fitted by aeroelastic model is more reasonable than section model's, it is difficult to conduct.

4. NONLINEAR VIV METHOD

Based on Scanlan's semi-empirical nonlinear mathematical models, a method for interpreting the test results of section model into prototype bridge was proposed by the author (Sun 2014), and the uncompleted correlation of vortex-induced aerodynamic force along span was considered in the method. The amplitude in the form of generalized coordinates was defined as following form:

$$\xi_0 = 2 \sqrt{\frac{\Phi_2}{\varepsilon' \Phi_4}} \left(1 - \frac{2\zeta K}{m_r \Phi_2 Y_1'} \int_0^L \phi^2(x) dx \right)^{1/2} \quad (4)$$

The VIV amplitude for considering the partial correlation can be obtained from $y(x) = \xi_0 \phi(x) D$. The express of reduced factors can be written as Eq. 5 and Eq. 6, and they can be calculated by self-convolution integration of mode shape.

$$\Phi = \sqrt{\frac{1}{L^2} \int_0^L \theta(\Delta x) R(\Delta x) d\Delta x} \quad (5)$$

$$\Phi_2 = \sqrt{\frac{1}{L^2} \int_0^L 2 \int_{-L/2}^{L/2-\Delta x} \phi^2(x) \cdot \phi^2(x+\Delta x) dx \cdot R(\Delta x) d\Delta x} \quad (6)$$

$$\Phi_4 = \sqrt{\frac{1}{L^2} \int_0^L 2 \int_{-L/2}^{L/2-\Delta x} \phi^4(x) \cdot \phi^4(x+\Delta x) dx \cdot R(\Delta x) d\Delta x}$$

As the reduced factor Φ is an amplitude dependent variable, the iterative process is needed. The VIV amplitude of prototype bridge under partial correlation can be estimated by following steps:

- (1) Conduct section model wind tunnel tests, and obtain VIV amplitude and lock-in wind velocity;
- (2) Identify VIV parameters Y_1 and ε by using experimental data, and $Y_1' = Y_1/\Phi$, $\varepsilon' = \varepsilon$;
- (3) Estimate VIV amplitude of the actual bridge by using Eq. 4 for full correlation case ($R = 1$);
- (4) Calculate reduced factors with Eq. 5 and Eq. 6 by using the calculated amplitude of the previous step;
- (5) Calculate the amplitude by using Eq. 4 with iterative method until convergence or meaningful amplitude is obtained. The amplitude dependent reduced factors included in Eq. 4 should be calculated by Eq. 5 and Eq. 6 in every iterative step.

The VIV amplitude of prototype bridge under partial correlation can be obtained after several iteration. More details about this method can be seen in (Sun 2014).

5. APPLICATION OF FITTED CORRELATION FUNTION

To verify the validity of the fitted correlation function, the VIV response of section model was interpreted into an aeroelastic model by applying a nonlinear VIV method in which the spanwise correlation of vortex-induced force was taken into consideration, and compared with the test results of simply supported aeroelastic model.

The test results of section model and simply supported aeroelastic model were listed in Table 1 and Table 2. The test results of two models cannot be compared with each other directly, as their damping and mass are quite different. The VIV amplitude of section model could be converted to any damping and mass system by using the logarithmic equation between VIV amplitude and Scruton number (Eq. 7).

$$\text{Log}A = a \cdot \text{Log}Sc + b \quad (7)$$

in which, A is VIV amplitude; Sc is Scruton number; $Sc = 4\pi\zeta m / \rho D^2$; a and b can be fitted by several tests. The converted results were listed in Table 3, the analytical results of other methods were listed as well.

Table 1 Test results of section model

Attack angle(°)	M (kg/m)	ζ (%)	Sc	A (%)	$\text{Log}(A)$	$\text{Log}(Sc)$
0	11.12	0.53	49.973	3.971	-1.401	1.699
	11.12	0.73	68.831	2.97	-1.527	1.838
	11.12	1.2	113.147	2.32	-1.634	2.054
	8.03	0.29	19.669	7.007	-1.154	1.294
3	11.12	0.53	49.973	6.459	-1.190	1.699
	11.12	0.73	68.831	4.987	-1.302	1.838
	11.12	1.2	113.147	3.633	-1.440	2.054
	8.03	0.29	19.669	12.22	-0.913	1.294

Table 2 Test results of simply supported aeroelastic model

Attack angle(°)	m (kg/m)	ζ (%)	A (%)	Sc	$\text{Log}(Sc)$
0	8.03	0.29	5.881	19.67	1.294
3	8.03	0.29	9.098	19.67	1.294

Table 3 The analytical results of different method

Method	0°	3°
Section model	7.007	12.22
$\frac{4}{\pi} A_m$ (Zhu 2005)	8.922	15.564
$\frac{2\sqrt{3}}{3} A_m$ (Zhang 2011)	8.091	14.115
Nonlinear VIV method	6.13	8.05
Aeroelastic model	5.88	9.098

It shows from Table 3 that if the section model test result is directly interpreted into prototype bridge, very conservative results may be yield. By using the traditional interpreting methods which only consider the effects of mode shape without taking the spanwise correlation of vortex-induced force into account may yield similar conclusion. It's obvious that a good consistency between section model and aeroelastic model is only found by considering the contribution of spanwise correlation of vortex-induced

force. And the fitted correlation function by section model tests can be adopted by the nonlinear VIV method to evaluate the amplitude of aeroelastic model.

5. CONCLUSIONS

If the section model test result is directly interpreted into prototype bridge, or only the effects of mode shape is considered without taking the spanwise correlation of vortex-induced force, conservative results may be yield. By considering the contribution of spanwise correlation of vortex-induced force, the test results of section model can be used to estimate the VIV performance of the prototype bridge.

It is more reasonable to get the correlation function by aeroelastic model, but it is difficult to conduct the test. For long-span bridge, it is acceptable to use the correlation function fitted from section model tests.

ACKNOWLEDGMENTS

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