An investigation on the VIV characteristics of parallel cable-stayed bridges with different spacings by aeroelastic model wind tunnel test

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SUMMARY:
In this paper, the VIV characteristics of parallel Π-shaped composite deck cable-stayed bridges with different spacings are systematically studied by aeroelastic model wind tunnel test and CFD simulation. The results show that the VIV characteristics of the parallel bridges can be divided into three regions according to the spacing ratio (*L*/*D*). For the region I (*L*/*D*=5~9.5), in which the downstream deck is greatly affected by the alternating vortex-shedding in its wake compared to the single bridge. The VIV amplitude of the downstream deck is amplified greatly and larger than the upstream deck. The lock-in region of the downstream deck is delayed obviously and the phase difference of upstream and downstream is greater than zero. For the region II (*L*/*D*=9.5~15), the wake vortex appearing alternately on the upstream deck makes its amplitude greater than the downstream, and the phase difference is less than zero; For the region III (*L*/*D*>15), the weakening of the interference effect makes the upstream and downstream decks have no obvious alternating shedding wake vortices. Therefore, their VIV characteristics are close to single bridges.

Keywords: parallel bridges, VIV characteristics, different spacings, Aeroelastic model test

1. INTRODUCTION

Previous studies showed that the aerodynamic interference effect deteriorates the VIV performance of the parallel bridges. The spacing is an important factor in determining the VIV characteristics of parallel bridges (Meng et al, 2011). At present, there are few studies on the VIV of parallel Π-shaped composite bridges. In this paper, the full-bridge aeroelastic model test and numerical simulation is carried out to study the VIV characteristics of parallel bridges with different spacing ratios.

2. INTRODUCTION TO RESEARCH METHODS

The full-bridge aeroelastic model test of parallel bridges was carried out in XNJD-3 Wind Tunnel, as show in Fig.1(a). The model scale is 1:80. It should be noted that the parameters, such as geometric dimension, the natural frequency and damping ratio of upstream bridge model are consistent with the downstream one. The parameters of the full-bridge aeroelastic models are listed in Table 1. The cross section of the bridge is shown in Fig.1(b). The spacing ratio *P* is defined as the ratio of the spacing *L* to the height *D*. The spacing between the upstream and downstream models are changed by adjusting the independent iron plates on which the model installed. 10 different spacing ratios *P* of 6, 7, 8, 9, 10, 12, 14, 16, 20 and 30 were investigated to study the VIV characteristics of the parallel bridges. It is worth noting that a single bridge case was firstly tested for reference. In addition, the two-dimensional flow field around the cross section under several typical spacings *P* of 8, 12 and 20 was simulated by ANSYS software. The computational domain layout and meshing are shown in Fig.1(c, d).

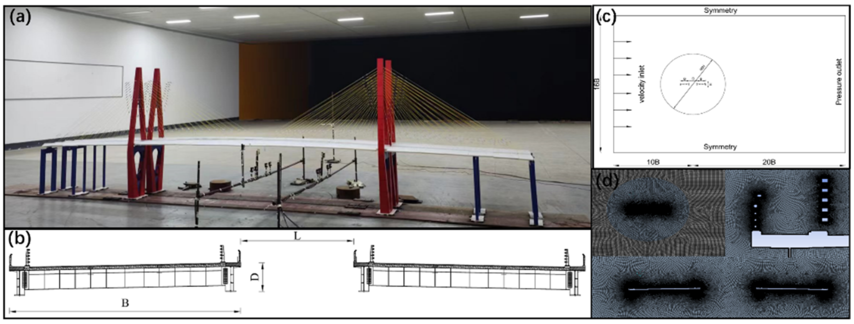

Figure 1. (a) Wind-tunnel test; (b) Cross-section of deck; (c) Computational domain; and (d). Grid division.

Table 1. Parameters of the aeroelastic model wind tunnel tests.

Item	Parameter	Unit	Upstream deck	Downstream deck
Equivalent mass	Mass, *m*	Kg/m	9.23	9.22
	Mass moment of inertia, J_m	Kg*m^2/m	0.171	0.170
Frequency	V-S-1	Hz	3.92	3.90
	V-A-1	Hz	4.87	4.86
	T-S-1	Hz	8.02	7.98
Damping ratio	V-S-1	%	0.76	0.78
	V-A-1	%	0.81	0.84
	T-S-1	%	0.85	0.83

Note: S- symmetrical; A-antisymmetric; V- vertical; T- torsional

3. FULL-BRIDGE AEROELASTIC MODEL TEST RESULTS AND DISCUSSION

3.1. Basic characteristics of VIV

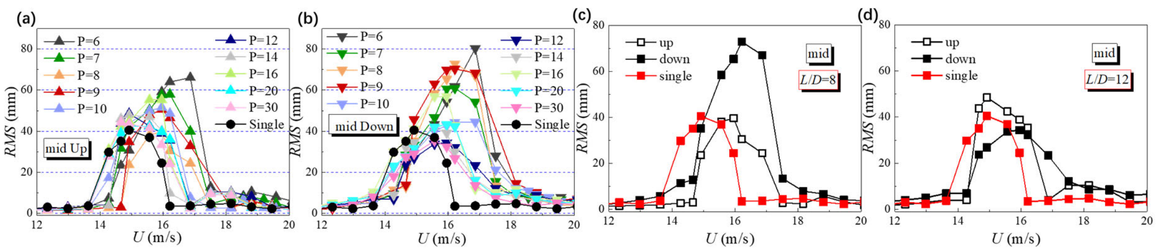

Figure 2. VIV amplitude: a. mid-span upstream; b. mid-span downstream; c. mid-span *L*/*D*=8; d. mid-span *L*/*D*=12

The testing results show that there are obvious vertical VIV responses at different spacings. No obvious torsional VIV was observed during the tests. Fig. 2(a, b) show the curve of the RMS amplitude of the decks at mid-span varying with mean wind speed for the parallel bridges with different spacing ratios. We can see that compared with the results of a single bridge, the aerodynamic interference effect is noticeable, which is greatly affected by the spacing ratio. In addition, the vertical VIV responses of the deck at quarter-span is similar to the deck at mid-span. Three typical spacing ratios (*L*/*D*=8,12,20) are selected to further explore the VIV characteristics of the parallel bridges. As shown in Fig.2 (c, d), the downstream amplitude is greater than the upstream amplitude when *L*/*D*=8. The lock-in region of downstream deck is obviously delayed. When *L*/*D*=12, the downstream amplitude is smaller than the upstream amplitude. The lock-in region is gradually close to the single bridge. When *L*/*D*=20, the aerodynamic interference effect is very small due to the large distance (the curve is not shown here).

3.2. VIV Characteristics of vibration state

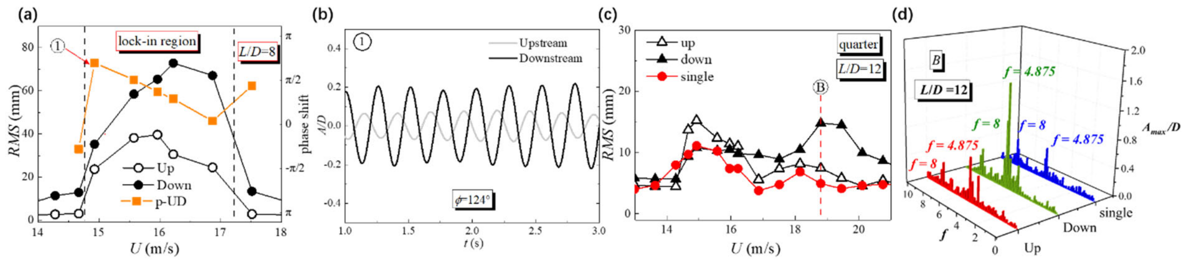

Figure 3. VIV characteristics: (a) phase difference mid -span *L*/*D*=8; (b) vibration time history mid -span *L*/*D*=8; (c) VIV amplitude at quarter-span of deck *L*/*D*=12; and (d) PSD analysis at quarter-span of deck *L*/*D*=12.

Through the above analysis, the VIV characteristics of the parallel bridges are complex compared to the single bridge. For the case of *L*/*D*=8, due to the aerodynamic interference effect, there is a phase difference in the VIV responses between the upstream and downstream bridge decks, as shown in Fig.3 (a, b). It is noted that the positive phase difference indicates that the upstream deck is ahead of the downstream deck. The phase difference decreases with the increase of wind speed in the lock-in interval. We can also find that there are obvious high-order VIVs at some spacings, such as the case of *L*/*D*=12. As shown in Fig.3(c, d), at the quarter-span, the vibration frequency is mainly 4.75 Hz (V-A-1) and 8 Hz (T-S-1), and the VIV amplitude of the downstream deck is obviously larger, which needs attention in practice engineering.

3.3. Influence of Spacing Variation on VIV Characteristics and the classification of spacing

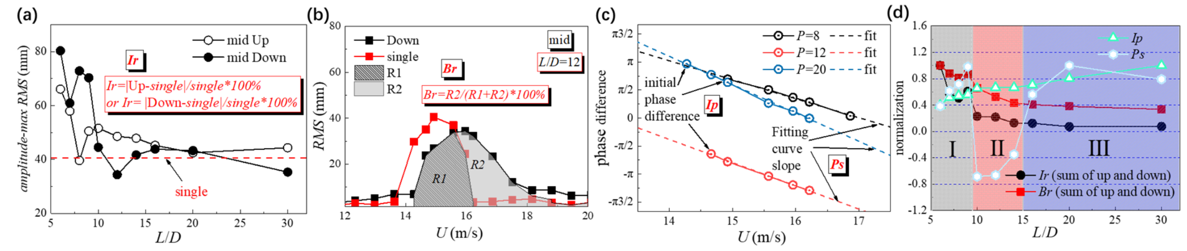

Figure 4. Aerodynamic interference parameters: (a) *Ir*; (b) *Br*; (c) *Ip* and *Ps* (d) region division

To deep address the influence of spacing on VIV characteristics, some parameters are defined to quantify the aerodynamic interference effect for further analysis, as illustrated in Fig.3 (a, b, c). Firstly, compared with the results of a single bridge, *Ir* represents the degree of change in the maximum amplitude. *Br* represents the proportion of the area of the vortex vibration region and the part (*R2*) that does not coincide with the single bridge in the amplitude wind speed curve, which comprehensively considers the deviation degree of the amplitude and the lock-in region. *Ip* and *Ps* represent the initial value of the phase difference and its rate of change. Fig.3(d) show the values of these parameters (normalized) at different spacing ratios. According to the variation law and gradient of these parameters, the spacing can be roughly divided into three parts : region I is the severely affected area (*L*/*D*=5~9.5), which is characterized by obvious amplification effect in the downstream, in addition, *Ip* is greater than zero and the *Ps* is relatively small; region II is the Moderately affected area (*L*/*D*=9.5~15), its characteristic is that the upstream amplitude is greater than the downstream and the *Ip* is less than zero; region III is the Mildly affected area (*L*/*D*>15), the large distance naturally makes its aerodynamic interference effect very small.

4. VIV MECHANISM DISCUSSION

In this section, the mechanism of VIV is studied by analysing the flow field structure around the bridge deck under typical spacing ratios. First, it can be found that with the increase of the spacing, the ' Ω ' and ' Ʊ ' flow field formed by the upstream wake shedding in the S region is gradually weakened. It can be clearly seen that the downstream region D3 has a more obvious alternative vortex-shedding when *L*/*D*=8. However, the alternative vortex-shedding exists in the upstream region U3 when *L*/*D*=12. This can explain the reason why the VIV amplitude of downstream deck in the region I and the VIV amplitude of upstream deck in the region II is much larger, as found in Section 3.

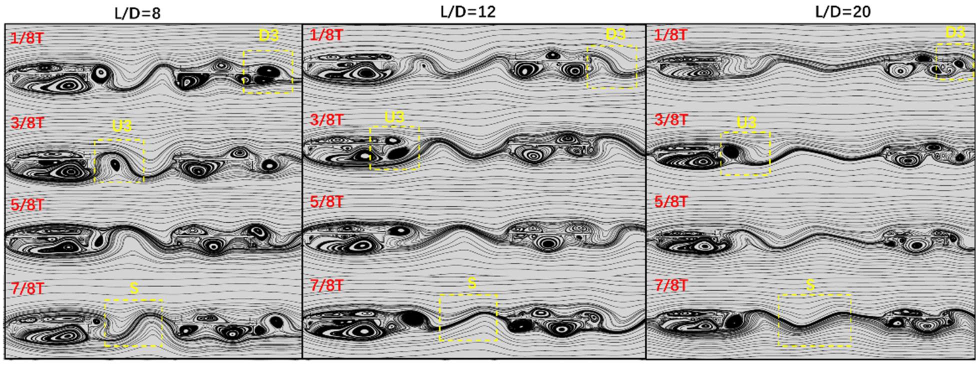

Figure 5. The flow structures around the cross-section under typical spacing ratios. (*L*/*D*=8,12,20)

5. CONCLUSIONS

The VIV characteristics of the parallel bridges can be divided into three regions according to their spacing ratios. Due to the influence of the alternating shedding wake vortex, the region I (*L*/*D*=5~9.5) has strong aerodynamic interference, and the downstream amplitude is large, however, in the II region (*L*/*D*=9.5~15), the aerodynamic interference effect is weaker and upstream amplitude is larger. The increase of distance makes the aerodynamic interference in the III region (*L*/*D*>15) is small, and the VIV characteristics are close to the single bridge.

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