Vortex-induced vibration in a parallel cable-stayed bridge

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Abstract

A vortex-induced vibration (VIV) has been observed in a parallel cable-stayed bridge. This study reproduces the vibration in a wind tunnel and investigates the source of the large amplitude VIV. A series of wind tunnel tests show that the main contribution of the vibration comes from the parallel disposition of two decks in a close distance. The flow field is observed with PIV tests with the phase averaging scheme.

1 Introduction

A vortex-induced vibration (VIV) has been observed in a parallel cable-stayed bridge. The maximum single amplitude was found to be almost 20 cm at the center of the main span. The bridge is composed of a streamlined steel box deck with 344 m in span length. Both the decks are equipped with guide vanes to mitigate the VIV. The performance of the guide vanes were satisfied with the design allowance for the case of single location. However, the parallel disposition seems to promote the VIV currently observed. The two bridges are very closely disposed, and the clear distance between each deck is shorter than a deck width (see Fig. 1). The center to center gap distance \( X \) is 22.25 m and the deck widths of investigated and proximate bridges are, respectively, 12.69 m and 11.86 m, then the ratio \( X/B \) is 1.75 ~ 1.88.

This kind of aerodynamic interference has been reported between closely spaced two decks (Honda et al., 1993; Larsen et al., 2000; Kimura et al., 2008). If the two bridge decks are close to each other, the behavior of VIV of one bridge deck will be affected by another deck. This parallel effect is sensitive to the ratio \( X/B \), and it is even serious with the ratio as much as 8 (Kimura et al., 2008).

Most of the previous researches concentrated on the aerodynamic performances of the parallel decks, and introduced interesting results. However it did not derive any general conclusion for parallel bridge behaviors. In order to confirm that the vibration of investigated bridge is originated from the parallel disposition of the decks, the flow field is observed in 2D wind tunnel with Particle Image Velocimetry (PIV).

![Diagram](image.png)

Figure 1: Girder section configuration (Guide vanes are not shown.)
2 VIV of Parallel Bridge Decks in a Wind Tunnel

A series of 2D wind tunnel tests was operated by the Department of Civil and Environmental Engineering at Seoul National University with 1/36 scaled section models. Table 1 shows dynamic parameters for the model setup. The dimensions including the gap distance and dynamic properties of the real bridges were reflected in section model by the law of similitude. The damping ratios are under-tuned in the experiments in order to emphasize the vibrations of decks.

The tests are mainly performed for 3 cases. In Case 1, the investigated bridge is tested alone. In Case 2, the investigated bridge is placed at windward while the proximate bridge is located at leeward. This case has the same wind direction as the VIV occurred for the actual bridge. In Case 3, the test is performed for the opposite wind direction. Thus the investigated and proximate bridges are set at the leeward and windward, respectively. All cases are performed in smooth flow. The test section of the wind tunnel is 1.0 m in width and 1.5 m in height.

Tests results are shown in Figure 2 with a prototype scale. In the parallel disposition (Cases 2 and 3), the maximum amplitudes of the investigated bridge are respectively 4.7–6.2 times larger than the single disposition (Case 1) in the vertical VIV. In Case 2, especially, VIV occurs at wind velocity of 12–14 m/s and that is similar to wind velocity for VIV of real bridge, 13–15 m/s. For the torsional VIV, parallel disposition amplifies the response for Case 3, while mitigates for Case 2.

Table 1: Dynamic parameters of the investigated and proximate bridges

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Investigated bridge</th>
<th>Proximate bridge</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Proto design</td>
<td>Model measured</td>
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<tr>
<td>Length (m)</td>
<td>32.4</td>
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</tr>
<tr>
<td>Width (m)</td>
<td>12.69</td>
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</tr>
<tr>
<td>Mass (kg/m)</td>
<td>8978</td>
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<tr>
<td>Mass moment of inertia (kg·m²/m)</td>
<td>152836</td>
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<tr>
<td>Vertical natural frequency (Hz)</td>
<td>0.436</td>
<td>2.180</td>
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<tr>
<td>Torsional natural frequency (Hz)</td>
<td>1.834</td>
<td>9.165</td>
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<tr>
<td>Vertical damping ratio (%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Torsional damping ratio (%)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2: (a) Vertical response of VIV according to wind velocity, (b) Rotational response
3 PIV Measurements

A series of vibration test clarifies that the aerodynamic characteristics of the bridge decks are influenced by aerodynamic interference due to parallel disposition of two bridge decks. In order to verify the VIV mechanism observed in the wind tunnel tests, flow visualization is required.

There was an attempt to investigate the flow patterns around the decks with CFD analysis (Meng et al., 2011). The research compares the flow patterns of two types of single deck which are, respectively, semi-closed box deck and single full-closed box deck with that of double semi-closed box decks. This study concludes that the flow around double decks is significantly different from that of single deck.

The PIV images could cover sufficient area for analysis at one time as long as the system is consisted of a laser with light intensity of 135 mJ at 15 Hz and a digital CCD camera with 2M pixel resolution at 15 fps (a maximum frame rate of 32). The flow fields at almost equally spaced 1/16 phases of one entire period were monitored during the steady-state lock-in heaving motion. The triggering of PIV capture was controlled by the amplified signal of a noncontact displacement transducer which monitored the motion of the investigated bridge. The repeated PIV pictures at one phase produced very similar flow patterns. Accordingly, 500 repeated images were saved and averaged at a specific phase to obtain a clear picture of the flow pattern between the two parallel bridge deck sections.

Figure 3 shows the flow around the double decks with the contour and streamlines while the downward motion. As the investigated bridge approaches the down position in a phase, the flow is entering the gap from the upside to the downside and results in a downward force on investigated bridge. Figure 4, however, shows the flow fields for the upward motion. Compared to downward motion, the flow comes from downside to upside and generates an upward force on investigated bridge. This phenomenon is observed repeatedly according to the bridge motion. An alternating eddies were observed at the top and bottom corners of the upstream deck in phase with the deck vibration. The generated eddies flowed down to the downstream deck and the subsequent wind streams were fed into the gap from the top and bottom corners of the investigated bridge. These alternating downward and upward flows excited the investigated bridge at the lock-in wind velocity and amplify the interference VIV in investigated bridge.

Figure 3: Flow fields during downward motion
4 Conclusion

The VIV for a parallel cable-stayed bridge is realized in a wind tunnel test. In order to confirm the resource of the VIV, three cases of comparative tests were performed. The simulated tests successfully demonstrated the VIV characteristics for the parallel bridges. The flow field is traced with a PIV test. The large eddies is confirmed at the gap between two bridge decks. This alternating vortex maybe the source of the amplification of VIV observed in the field monitoring.

Acknowledgements

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References


