Flow measurement of vortex-induced vibration of parallel bridge girders by PIV

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ABSTRACT: A vortex-induced vibration has been observed in a parallel cable-stayed bridge. In order to understand the aerodynamic behavior of the bridge, a series of wind tunnel tests was performed. The flow around the decks is investigated with the help of a Particle Image Velocimetry.

KEYWORDS: parallel bridge, vortex-induced vibration (VIV), particle image velocimetry (PIV), wind tunnel test, flow measurement

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).

![Figure 1. Girder section configuration (Guide vanes are not included)](image-url)
2 VIV OF PARALLEL BRIDGE DECKS

A series of 2D wind tunnel tests was performed with 1/36 scaled section models. The dimensions including the gap distance and dynamic properties of the real bridges were reflected in section model by the law of similitude. Table 1 shows dynamic parameters for the model setup.

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. The damping ratios are under-tuned in the experiments in order to emphasize the vibrations of decks. In Cases 2 and 3, the maximum amplitudes of the investigated bridge are respectively 4.7~6.2 times larger than 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 effect increases the displacement for Case 3, while decreases for Case 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Investigated bridge</th>
<th>Proximate bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proto</td>
<td>Model</td>
</tr>
<tr>
<td>Length (m)</td>
<td>32.4</td>
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<tr>
<td>Width (m)</td>
<td>12.69</td>
<td>0.353</td>
</tr>
<tr>
<td>Mass (kg/m)</td>
<td>8978</td>
<td>6.927</td>
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<tr>
<td>Mass moment of inertia (kg·m²/m)</td>
<td>152836</td>
<td>0.091</td>
</tr>
<tr>
<td>Vertical natural frequency (Hz)</td>
<td>0.436</td>
<td>2.180</td>
</tr>
<tr>
<td>Torsional natural frequency (Hz)</td>
<td>1.834</td>
<td>9.165</td>
</tr>
<tr>
<td>Vertical damping ratio (%)</td>
<td>-</td>
<td>0.100</td>
</tr>
<tr>
<td>Torsional damping ratio (%)</td>
<td>-</td>
<td>0.100</td>
</tr>
</tbody>
</table>

Figure 2. Wind velocity and amplitude of VIV
3 FLOW MEASUREMENT BY PIV

There is no doubt that the aerodynamic characteristics of the bridge decks are influenced by aerodynamic interference due to parallel disposition of two bridge decks. In order to interpret the VIV mechanism observed in the wind tunnel tests, flow visualization is required.

There was an attempt to show 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. It says that the flow around double decks is significantly different from that of single deck. According to the CFD results, the paper anticipates that the VIV resonances of bridges, especially for leeward one, would be magnified if the both bridges have same aerodynamic configuration and natural frequencies, but if not, in contrast, the VIV resonances would be non-synchronous and weakened. The investigated bridge and proximate bridge have similar shapes and frequencies and, as a result, the VIV is anticipated as was observed.

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 sampling rate is not high enough to get the very clear procedure of VIV formation. This problem may be enhanced in further study with a triggering technique for a series of divided target phases.

Figure 3 shows the flow around the single bridge deck. The contour represents the magnitude of velocity vector and the white lines denote the streamlines. It can be seen that the flow separation occurs alternately from the top and bottom of the deck, and then moves to leeward for a certain distance, converging into one flow. For this reason, a triangular area is obviously observed right behind the deck where the flow velocity is nearly zero.

Figure 4 shows the flow around the double decks with the contour and streamlines. It can be seen that the flows suddenly converge right behind the windward deck, and stirs up the gap space then moves to leeward side. In this situation, additional large eddies are generated in the gap space. The rotational direction of eddies keep changing periodically, and accordingly, the direction of flow streams changes up and down alternately. This will be the source of VIV excitation.
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 VIV observed in the field monitoring.

5 ACKNOWLEDGEMENTS
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6 REFERENCES