Wind-tunnel study for effects of vehicles on bridge aerodynamics

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This study is intended to investigate traffic effect on the aerodynamic stability of bridge deck. Wind tunnel tests have been conducted to test 3 different scaled bridge section models with vehicle models arranged on the bridge decks considering different types of traffic flows. The influence of vehicles of different traffic flows under cross wind on the aerodynamic performance of the bridges with the reduced wind velocity are investigated based on the experimental results. By comparing the measured results, the influence of vehicles on the aerodynamic stability of the bridge is overall not significant except some large vehicle and multiple arrangement cases.

Keywords: bridge aerodynamic stability, vehicle effect, wind tunnel test

1. INTRODUCTION

Economic development increases the traffic volume significantly over bridges and roads during these years. Vehicles, especially heavy vehicles on bridge may change the local dynamic behavior and affect the fatigue life of the bridge. When the wind load is also applied on this bridge-vehicle system, further undesired vibration will be generated1-2).

In most aerodynamic study of long-span bridges, the effect of traffic on a bridge deck are not typically considered, assuming that the bridges will be closed under severe windy conditions. Suzuki et al.5) carried out three kinds of wind tunnel tests to obtain the aerodynamic characteristics for typical configurations of vehicles on bridges and embankments. Li et al.6) developed a special device, called the Cross Slot System, to measure the aerodynamic interaction of the train-bridge system, taking into account the aerodynamic interaction between train cars and bridge. Han et al.7) evaluated static force coefficients by a CFD method and wind-tunnel test. But the truth is that long-span bridges which are located in coastal and mountainous areas are easily affected by high cross wind. When vehicles stop on bridge deck during traffic congestion and/or an accident under strong cross wind conditions, aerodynamic performance of bridge deck will be influenced8).

There are not so many studies for vehicle effects on bridge aerodynamic characteristics under different traffic flows where many vehicles are arranged in different ways. Since there is no standard to analyze the effect of random distribution of vehicles on a bridge deck, definite conclusions cannot be drawn.

This study focuses on experimental investigation of the aerodynamic performance of three different deck models under various traffic flows.

2. WIND TUNNEL TEST

The wind-tunnel test adopts a spring-supported section model test. A series of cases were carried out to examine the aerodynamic characteristics of vehicle-bridge systems in the closed circuit wind tunnel at Yokohama National University. Section dimension of the wind tunnel is 1.8m wide and 1.8m high. All measurements were undertaken in static conditions (i.e., with no vehicle movement) under cross wind with angle of attack of 0 degree. The tests were carried out all in smooth flow with turbulence intensity of less than 0.3%.

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2.1 Bridge deck and vehicle models

Three different bridge section models are used in the test: 1) a hexagonal section model with a scale of 1:50 with 2 lanes on each side of bridge deck, 2) an edge girder deck with a scale of 1: 70 with 2 lanes on each sides and 3) a box girder with a relatively high depth-width ratio with a scale of 1:50 with 2 lanes and 1 pedestrian lane as shown in Fig. 1. This study considers aerodynamically sensitive bridge deck with which the span length is more than about 100m.

Five different vehicle models: (a) lorry, (b) passenger car, (c) bus, (d) truck and (e) SUV are considered and made with urethane foam to reduce the weight. Dimensions of vehicle models are given in Table 1 and Fig. 2.

Test cases were designed by considering location of vehicles (windward or leeward side, outer or inner lane), number of vehicles, combination of small and large vehicles, etc.

<table>
<thead>
<tr>
<th>Table 1 Dimensions of vehicle models in scale 1:50</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Length (mm)</td>
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<tr>
<td>Width (mm)</td>
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<tr>
<td>Height (mm)</td>
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</tbody>
</table>
2.2 Test conditions

Each bridge deck model was supported by simulated springs with a 2DOF vibration system in the wind tunnel. Vibration displacement of the model was measured using 2 laser displacement meters. Structural damping of logarithmic decrement was assumed approximately 0.03 (open deck) and 0.02 (closed deck) in vertical and 0.02 in torsional directions. However torsional damping could not be adjusted precisely because of device mechanism. Since this study is comparatively carried out, the adjustment error in torsional damping is negligible. All the measurement was done in smooth flow. Wind-tunnel test conditions are shown in Table 2.
Table 2 Wind tunnel tests conditions of each bridge deck models

<table>
<thead>
<tr>
<th></th>
<th>Hexagonal deck</th>
<th>Edge girder</th>
<th>Box girder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model scale</td>
<td>1: 50</td>
<td>1: 70</td>
<td>1: 50</td>
</tr>
<tr>
<td>Deck width $B$ (m)</td>
<td>0.434</td>
<td>0.379</td>
<td>0.245</td>
</tr>
<tr>
<td>Deck height $D$ (m)</td>
<td>0.041</td>
<td>0.043</td>
<td>0.069</td>
</tr>
<tr>
<td>Mass (kg/m)</td>
<td>8.00</td>
<td>4.44</td>
<td>7.529</td>
</tr>
<tr>
<td>Polar moment of inertia (kg m$^2$/m)</td>
<td>0.174</td>
<td>0.071</td>
<td>0.0761</td>
</tr>
<tr>
<td>Vertical frequency: $f_h$ (Hz)</td>
<td>1.76</td>
<td>1.71</td>
<td>2.61</td>
</tr>
<tr>
<td>Torsional frequency: $f_\theta$ (Hz)</td>
<td>2.71</td>
<td>3.58</td>
<td>5.71</td>
</tr>
<tr>
<td>Structural damping (Vertical): $\delta_h$</td>
<td>0.0172</td>
<td>0.0336</td>
<td>0.0211</td>
</tr>
<tr>
<td>Structural damping (Torsional): $\delta_\theta$</td>
<td>0.0080</td>
<td>0.0195</td>
<td>0.0202</td>
</tr>
</tbody>
</table>

3. TEST RESULTS OF EACH BRIDGE DECK

3.1 Hexagonal deck

In the basic case, the hexagonal deck model without vehicles was tested at the angle of attack of 0 degree. Fig. 4 shows vibration amplitude under different reduced wind speeds. It can be seen that there is no vertical vibration in low wind velocity range but at around reduced wind speed of 0.9 and 1.5, torsional vibration have been observed. Fig. 5 (i) shows the critical flutter wind speed in each case where torsional vibration amplitude reaches 2 degrees. It is obvious that the critical wind speed is affected by vehicle(s), particularly multiple large vehicles such as cases 30 and 31 in which vehicles are a barrier in the outer lane of windward as shown in Figs. 5 (ii) and (iii).

Figs. 6 (i) and (ii) show the vortex induced vibration (VIV) amplitude and corresponding lock-in wind velocity in each case. Except cases 6 and 34, it can be seen that the amplitude of torsional vibration increases in all of the cases when compared with no vehicles case. The amplitude of vortex induced vibration in each case has increased but not very much. The change of aerodynamic profile of the bridge deck with the presence of traffic increased the maximum VIV amplitude in each cases.

In addition, the lock-in wind speed increases in all of the cases except case 32 as shown in Fig. 6 (ii). When single and double vehicles applied on the deck, the lock-in wind speed is around 0.8, which is insignificant of vehicle effect. However, from cases 14 to 31, the lock-in wind speed increases to 1.2, in which multiple vehicles is applied on deck. This phenomenon is probably due to the increase in the number of large vehicles which will change the flow field around bridge deck considerably.

Fig. 7 shows effects of vehicles on torsional vibration amplitude by (i) single vehicle and (ii) multiple vehicles. In the case of one vehicle, a large lorry and bus increased torsional VIV amplitude more than small size car case, however flutter critical wind speed is not influenced much as shown in Fig. 7(i). The bus, which has a largest size, decreased the critical wind speed relatively largely.

In the case of multiple vehicles, large vehicles increased torsional VIV amplitude and decreased flutter critical wind speed as shown in Fig. 7(ii). In particular, flutter critical wind speed is influenced by windward arrangement (Fig. 7(iv)) more than multiple vehicle cases (Fig. 7(iii)). It is probably understood that the separation flow at the leading edge and vehicles directly affects the bridge deck in the windward arrangement. On the other hand, multiple small vehicle arrangement (Fig. 7(v)) does not influence torsional VIV amplitude nor flutter critical wind speed. In the single vehicle cases, the effect of the gap between vehicle and bridge deck was also conducted by comparing with gap and no gap groups. According to test data, the gap only slightly influenced the critical wind speed of bridge deck which is almost negligible, so we do not discussed the gap effect here.
(i) Vertical ($\Delta h/h$ is the vertical displacement relative to deck height)  
(ii) Torsional

**Fig. 4** Hexagonal deck without vehicle vibration

(i) Critical wind speed of flutter of hexagonal deck

(ii) Cases 30

(iii) Case 31

**Fig. 5** Critical wind speed of flutter of hexagonal deck with large vehicles in windward side (cont.)
(i) Torsional vortex induced vibration amplitude of hexagonal deck

(ii) Lock-in wind velocity

Fig. 6 Vortex-induced vibration amplitude and corresponding lock-in wind velocity

(i) Effect of single vehicle

(ii) Effect of multiple vehicles

(iii) Multiple vehicles case

(iv) Large vehicles in windward

(v) Small car case

Fig. 7 Vortex induced vibration degree and corresponding lock in wind velocity
3.2 Edge girder deck

Fig. 8 show vibration amplitude of the edge deck model without vehicles at angle of attack of 0 degrees. It can be seen that there is vertical VIV in low wind velocity between 1.8 and 2.9. Torsional VIV occurs at the reduced wind speed range between 1.5 and 2.1, and torsional flutter occurs at the reduced wind speed of around 3. Comparisons of the maximum VIV amplitude are shown in Fig. 9. Note that single vehicle cases are separately shown as the case number is the sequence of the test execution.

Due to the insignificant effect of double vehicle cases of the Hexagonal deck girder, double vehicle cases were not taken into consideration.

Vehicles on the bridge increase the amplitude of vertical VIV and multiple vehicle cases increase the amplitude larger than single vehicle cases. On the contrary, torsional VIV is suppressed by vehicles, in most cases of arrangement (except case 48). Similarly to the hexagonal deck case, multiple vehicle cases have larger influence on the bridge deck aerodynamics.

3.3 Box girder deck

The box girder deck without vehicles was tested at the angle of attack of 0 degrees. Figs. 10 (i) and (ii) show vibration amplitude under different reduced wind speeds. It can be seen that there is vertical VIV in low reduced wind speed range between 2 and 2.3, and 2.8 and 3.3. Torsional VIV have also been observed at the reduced wind speed range between 3 to 3.5 and torsional flutter occurred at the reduced wind speed after 6.

In Fig 11, it can be seen that for the box girder deck, multiple vehicle cases increase vertical VIV amplitude larger than single vehicle cases while torsional VIV amplitude decreases in general. This is the similar trend to the results in the edge girder deck.
4. CONCLUSIONS

This study conducted the experimental work to investigate the aerodynamic effects caused by vehicle arrangement on three different bridge deck models: the hexagonal box deck, the edge girder deck and the box girder. To simulate different traffic arrangements, various types of vehicle scaled models were used.

In the case of a hexagonal deck, large vehicles on the outer lane, especially in windward side, have larger influence to reduce the flutter critical wind speed of bridge. On the other hand, vehicles did not influence vortex induced vibration amplitude so much, likely, the lock-in wind speed is increased in those cases where large vehicles are on the bridge deck. This is probably due to that hexagonal is aerodynamically sensitive, and the critical wind speed and VIV are easily affected by the large vehicles on the deck.

In the cases of the edge girder deck and box deck, vehicles on the bridge increase the amplitude of vertical VIV and multiple vehicle cases increase the amplitude larger than single vehicle cases. On the contrary, torsional VIV is suppressed by vehicles, in most cases of arrangement. Similarly to the hexagonal deck case, multiple vehicle cases have larger influence on the bridge deck aerodynamics. It is concluded that this is probably caused by vehicle changing flow fields and vortex intensity around the deck. Details should be investigated in the future.

References

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