

Effects of balusters on vortex-induced vibration of a bluff bridge deck section

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ABSTRACT: The vortex shedding response of a bluff bridge girder deck with and without balusters has been investigated by numerical simulation and wind tunnel experiments with the objective of identifying the mode of vortex excitation and effects of balusters on vortex-induced vibration of bridge deck. Tests on 2 spring suspended models revealed different vortex response. This process is likely to render the blunt bridge girder deck with balusters more susceptible to vortex shedding excitation than the bare section. Measurement of the fluctuating pressure around the deck surface indicates that vortices shed from the downstream section with balusters have greatly contributed to the vertical vortex-induced vibration, while the bare section (i.e. without balusters) pressure fluctuations over the entire upper and lower surface have little contribution to the vortex response.

KEYWORDS: Bluff bridge deck; Balusters; Vortex-induced Vibration; Fluent; Wind tunnel test; Surface pressure measurement

1 INTRODUCTION

Vortex-induced vibration which is prone to occur is one of the wind-induced vibration phenomenon. For many years, lots of researchers have fully proved that the vortex response has a strong dependence on the shape of structures. Kubo et al. ^[1] had investigated the air flow characteristics of the torsional vortex-induced vibration of a π section with $C/D = 0.5$ and $C/D = 2$, where C is the length of the cantilever and D is the π section height. The results show that the flow separation in the $C/D = 0.5$ is more obvious than $C/D = 2$, that is, the more blunt π section is, the more serious separation. Nagao and co-workers ^[2] studied effects of handrails on the vortex-induced oscillations, the conclusion is that the handrails can amplify the vertical vortex-induced vibration, and in torsional vortex-induced vibration, the interaction of the separated flow and handrails can not only weaken the formation of vortices shedding, but also reduce the self-excited forces.

In order to analyze influences of balusters on vortex response of the bridge deck, this present paper makes a research on vortex-induced vibration response of a bluff bridge girder deck with and without balusters, and explains the differences of both vortex response through an analysis of surface pressure distribution.

2 VORTEX EXCITATION OF BRIDGE DECKS

The test section is based on a bluff bridge deck section with flanges (Fig. 1). As a trapezoidal box shape, Von Karman type vortices are expected to form and to be shed at regular time intervals in the downstream box as illustrated in the snapshots taken from a detached eddy simulation of the air flow, Fig. 2.

Fig. 2 indicates that the flow separation of two kinds of section is fairly different. The balusters have a great impact on the vortex shedding. Vortices of bare section are much less than vortices of section with balusters. The vortex shedding process of section with balusters may, if could allow to occur, lock-in with a vertical eigenmode, and thus excite vertical vortex-induced oscillations.

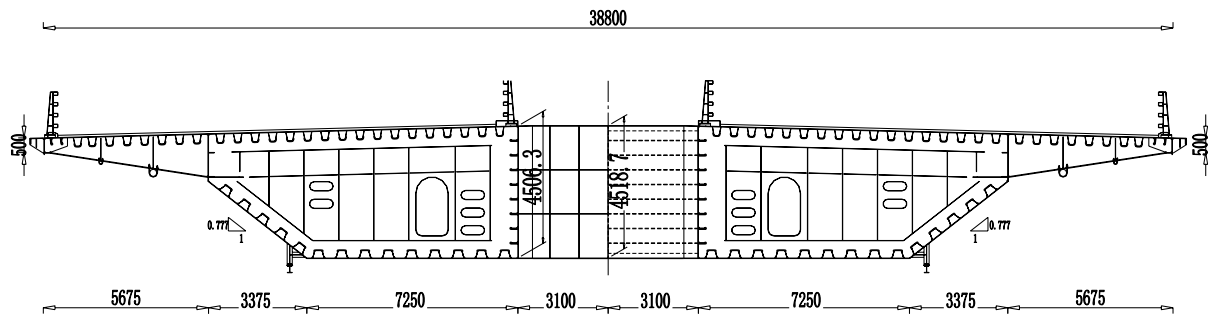


Fig. 1. Section of a box bridge girder. 38.8 meters wide (B), 4.5 meters high (H), the aspect ratio $H/B = 1:8.62$. There are four balusters with the height of 1.5m along the bridge cross section.

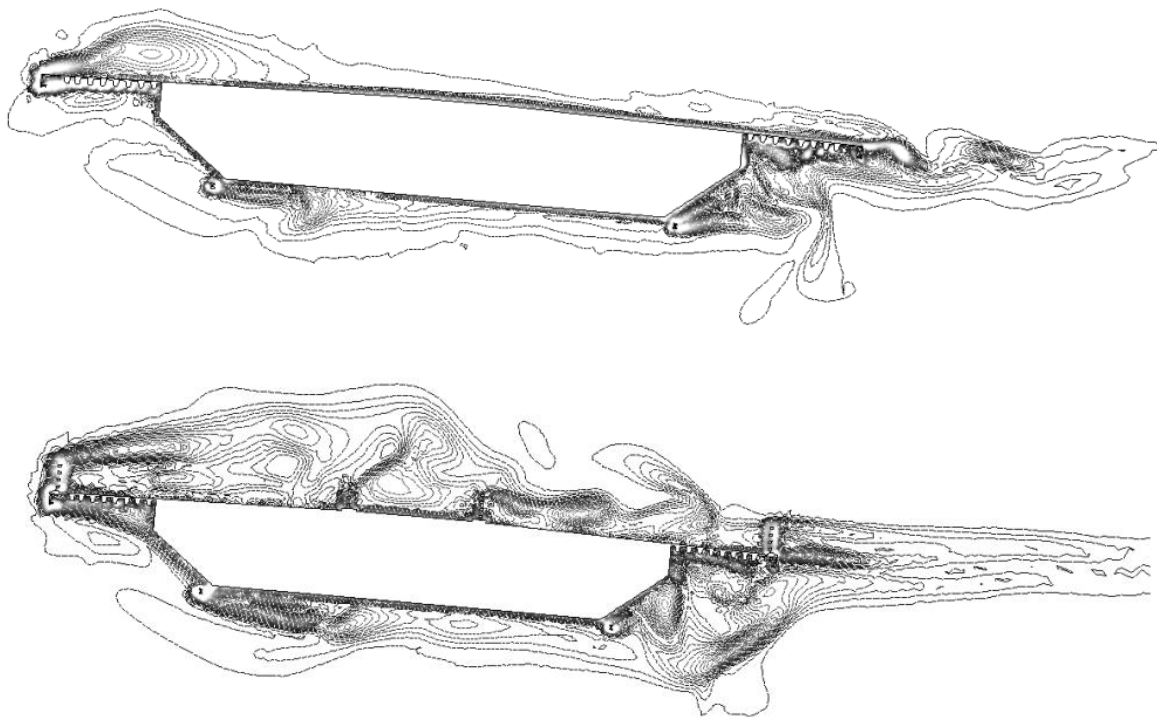


Fig. 2. Detached eddy simulation of the air flow about the bridge deck cross section with and without balusters. Angle of attack $\alpha = +5^\circ$, wind speed is 15 m/s. Bare section, i.e. without balusters (top), section with balusters (bottom).

3 VERTEX SHEDDING TESTS

The vortex response of two sections, as shown in Fig. 3, were test during standard 1:20 scale section model wind tunnel experiments conducted in CA-1 wind tunnel which is a closed circuit wind tunnel with test section of $3.0\text{m} \times 2.5\text{m}$. Tests on the section with balusters under the uniform flow revealed a vertical response peak of 5% root mean square (rms) amplitude of the section depth H at a non-dimensional wind speed $U/fB \approx 1.88$, while no vertex-reduced vibration happened in the bare section. Experimental studies had shown that the section with balusters excited two lock-in districts of vertical vortex-induced vibration. Larsen and his co-workers [3] also obtained the similar results in a 1 : 80 scale wind tunnel tests of a twin box bridge deck section.

The present paper focuses on the latter vortex-reduced vibration because the latter amplitude is fairly larger than the former. In order to understand the vortex response difference of the two sections, surface pressure measurements should be conducted.

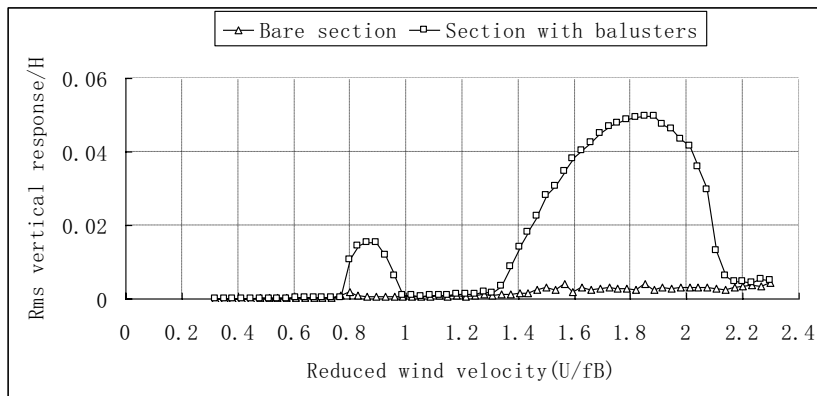


Fig. 3. Vortex response of the two kinds of section. 1:20 scale section model is supported by a 4.04 Hz spring suspension having a nominal structural damping $\zeta = 0.3\%$ relative-to-critical. Angle of attack $\alpha = +5\text{deg}$, U is wind speed, f is vertical frequency and B is the overall deck width.

4 SURFACE PRESSURE MEASUREMENTS

The surface fluctuating pressure status gave an opportunity to look further into the vortex dynamics through high frequency pressure measurements made at 120 taps (Fig. 4) mounted with the box section circumference. Two electronic pressure scanning valves manufactured by the PSI company in U.S were used to measure the fluctuating pressure around the two kinds of section. The range of each electronic pressure scanning valve is ± 10 inch water column. There are 64 channels on a single valve and the measurement time delay is not greater than $3.2 \times 10^{-3}\text{s}$, it is considered that every channel is measured simultaneously.

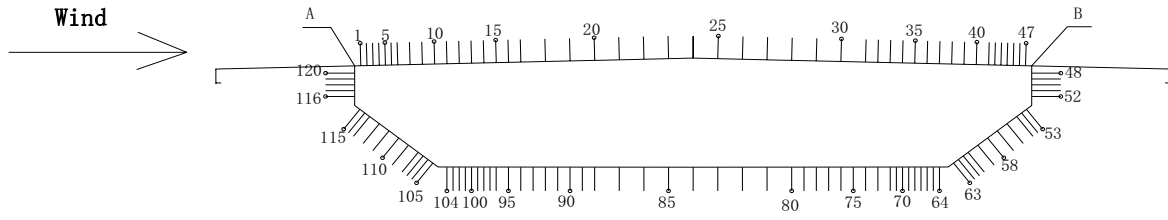


Fig. 4. Arrangement of pressure taps.

4.1 Mean pressure coefficient

Fig. 5 compares the mean pressure coefficient between the bare section and section with balusters at the non-dimensional wind speed $U/fB \approx 1.88$. The presence of balusters does not change the mean pressure distribution of soffit plate (Fig. 5 bottom), but significantly change the pressure distribution on the upper surface (Fig. 5 top). When introducing the balusters it is noted that the adverse pressure gradient on the upper surface ($x/D \approx 0.25 \sim 0.76$) of bare section vanish. In other words, the air flow separation on the upper surface come earlier owing to effects of balusters. Boundary layer separation would lead to vortex shedding, and vortex-induced forces from periodic vortex shedding would have contributed to the vortex-induced oscillations.

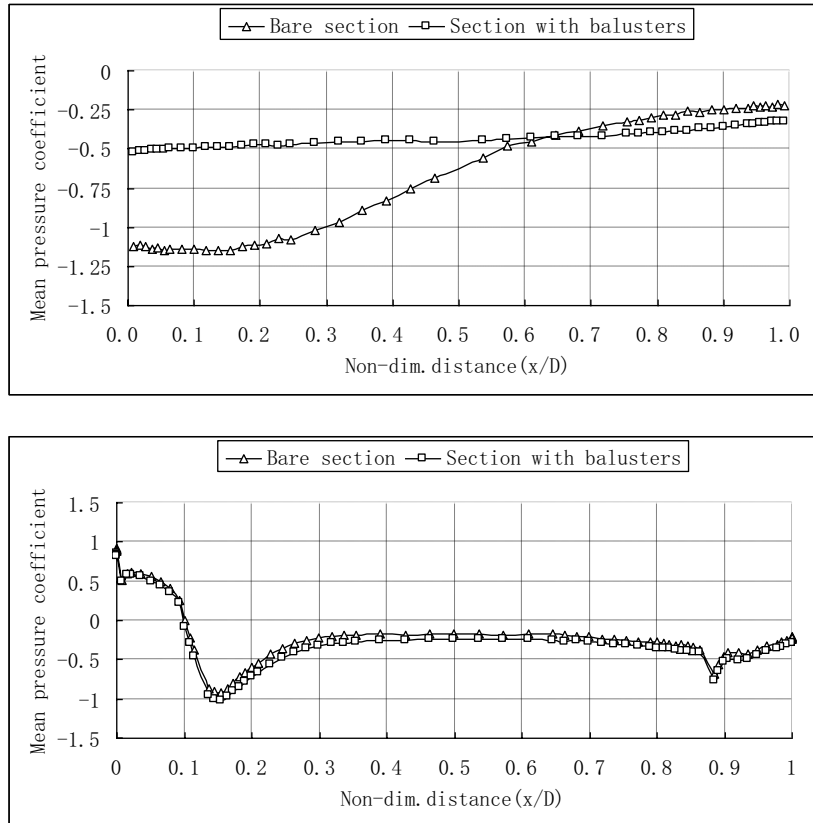


Fig. 5. Mean surface pressure coefficient of the two kinds of section at $U/fB \approx 1.88$. Upper surface (top) and lower surface(bottom).

4.2 Rms pressure coefficient

With reference to the response diagram in Fig. 6, corresponding normalized rms pressure coefficient distributions obtained for the bare section and the section with balusters were obtained through the calculation of surface pressure time-history of every tap. Analysis of the rms pressure coefficient can find the critical region of vortex-induced vibration. In particular, fairly large rms pressures which result from the adverse pressure gradient are observed on the central upper surface of bare section ($x/D = 0.32 \sim 0.68$). Observing the difference between the bare section and section with balusters rms pressure coefficients, it is noted that the strong pressure fluctuation of bare section on the upper surface vanish due to the existence of the balusters, but the fluctuating pressures are significantly increased in the downstream zone of the upper surface, especially in the region $x/D = 0.76 \sim 1.00$. When introducing the balusters it is noted that the pressures on the entire lower surface are markedly increased. The Rms pressure coefficients of the entire lower surface have increased by 2 times when going from no balusters to having balusters. Comparing the downstream zone pressure distributions for the bare section and section with balusters, it is evident that the presence of balusters has strengthened the pressure fluctuation significantly, giving evidence that the downstream zone of deck have great contribution to the vertical vortex-induced response.

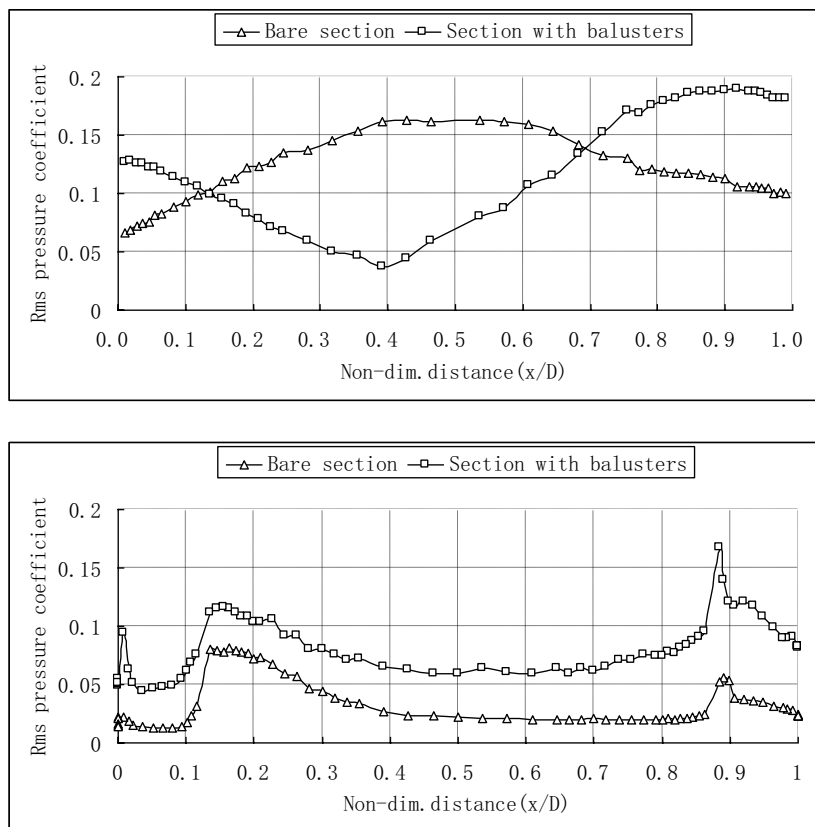


Fig. 6. Rms surface pressure coefficient of the two kinds of section at $U/fB \approx 1.88$. Upper surface (top) and lower surface(bottom).

5 AERODYNAMIC FORCES

In this paper, aerodynamic forces in wind-axis coordinate system were obtained from the recorded pressure signals by using a method of surface pressures integration^[4]. Aerodynamic force of a single pressure tap means aerodynamic force of the area which the tap represents, the total aerodynamic force is got by summarizing all the single taps.

Fig. 7 compares lift force time-history between bare section and section with balusters, and the curves of lift force power spectral density are shown in Fig. 8. For the section with balusters, a sinusoidal curve of lift force is shown in Fig. 7 (right) and a 4.04Hz harmonically lift force is noted in Fig. 8 (right). When the balusters are removed, Fig.7 (left) and Fig. 8 (left), the sinusoidal lift force and the distinct harmonic lift force altogether disappear, bearing evidence that the aerodynamic force of exciting vertical vortex-induced vibration is lift force. Vertical vortex-reduced vibration can be study through analysis of the changing of lift force because the vibration is caused by lift force.

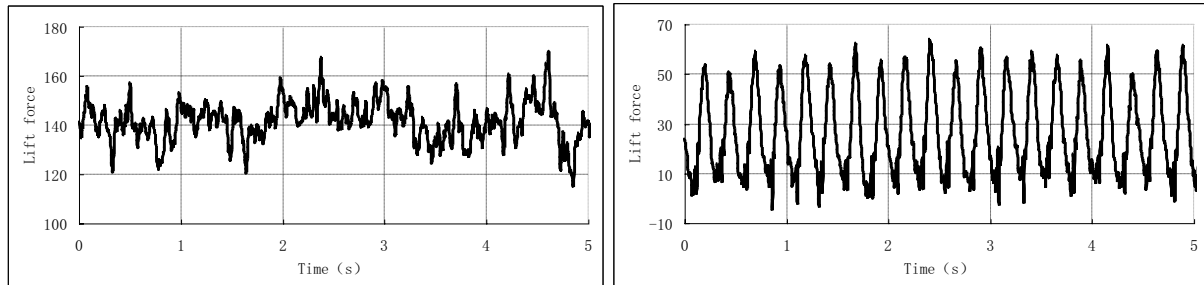


Fig. 7. Lift force time-history of the two kinds of section at $U/fB \approx 1.88$. Bare section (left) and section with balusters (right).

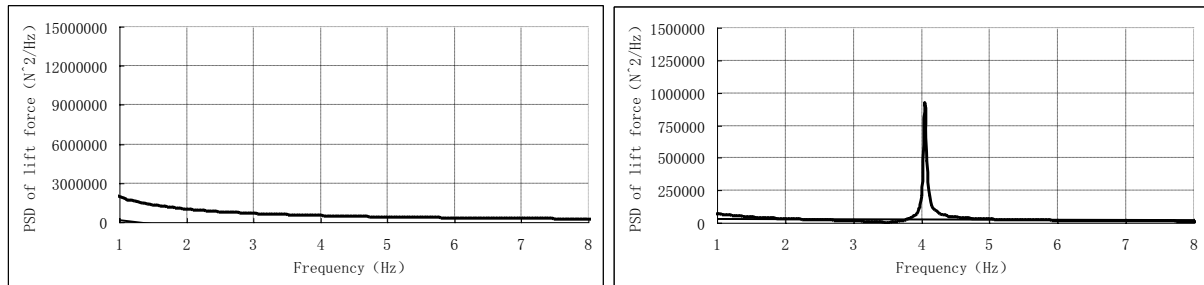


Fig. 8. Lift force power spectral density of the two kinds of section at $U/fB \approx 1.88$. Bare section (left) and section with balusters (right).

Fig. 9 shows Karl Pearson correlation coefficient between local lift force and total lift force. The contribution of the local lift force to vortex-reduced vibration, as shown in fig.10, can be obtained through the multiplication of local rms lift force and the correlation coefficient between local lift force and total lift force.

From Fig 9 it is noted that the correlation between local lift force and total lift force in the downstream zone have markedly increased due to the role of balusters. For the section with balusters, as shown in Fig. 10, the upper surface of the region $x / D = 0.68 \sim 0.99$ and the lower surface of the region $x / D = 0.35 \sim 0.98$ have a greater contribution to vertical vortex-reduced vibration, and the contribution of upper surface is significantly larger than the lower surface.

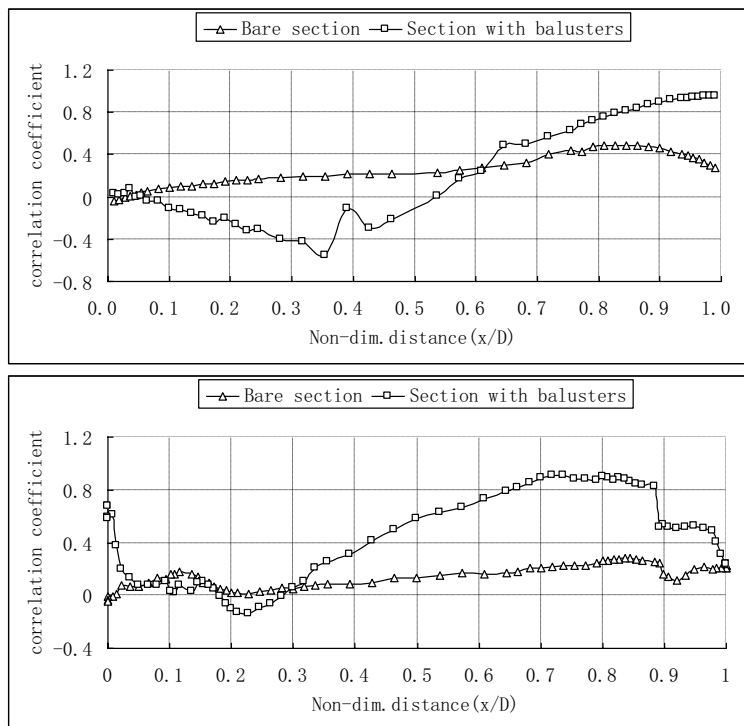


Fig. 9. Karl Pearson correlation coefficient of local lift force and total lift force at $U/fB \approx 1.88$. Upper surface (top) and lower surface (bottom).

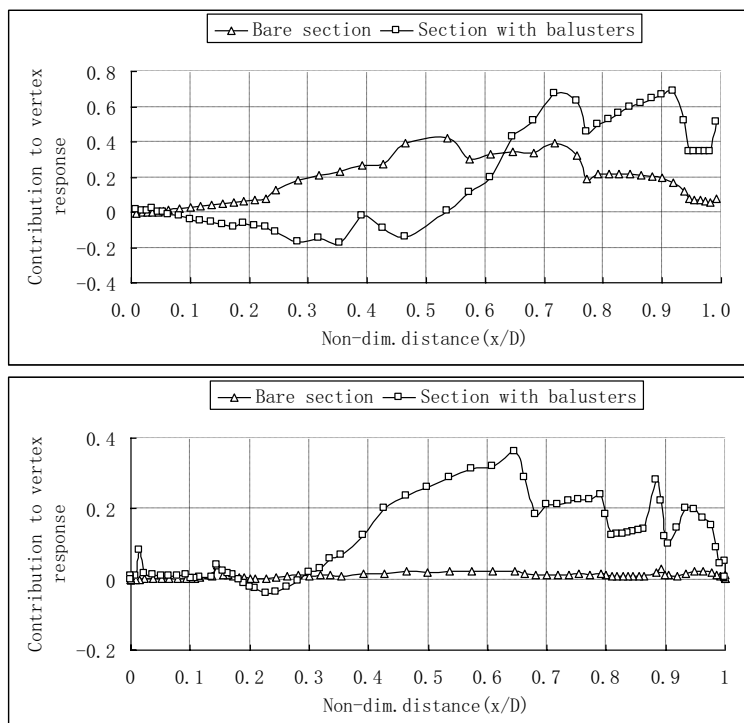


Fig. 10. Contribution of the local lift force to vortex-reduced vibration at $U/fB \approx 1.88$. Upper surface (top) and lower surface (bottom).

6 CONCLUSIONS

The present paper has examined vertical vortex response of a bluff bridge deck with a view to unveil the excitation mechanism of balusters on vortex-induced vibration of bridge deck. The following is concluding remarks about vortex response of the bridge deck section with and without balusters.

1) The balusters of bridge deck significantly affect the mean pressure distribution of the upper surface, but the lower surface mean pressure distribution will not be change by balusters. The balusters of bridge deck will not only dramatically affect the upper surface pressure fluctuation but also the lower surface pressure fluctuation.

2) It is concluded that vortex excitation of deck with balusters is likely to be stronger than vortex excitation of bare deck, as the deck with balusters fluctuating pressures originating from the vortex impinging on the downstream box are larger than the fluctuating pressures of bare deck.

3) The balusters of bridge deck stimulate the vertical vortex-reduced vibration. It may achieve the purpose of suppression of vortex-induced vibration through partially sealing the balusters. In order to verify the suppression effect of partially sealing the balusters, it is necessary to carry out wind tunnel tests.

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