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Multi-mode vortex-induced vibration of a long-span bridge under non-uniform flows

Wen-Li Chen [1,2], Siwen Sun [1,2], Wenhan Yang [1,2]

[1] Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin, 150090 China
[2] Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, 150090 China

SUMMARY:
With the increasing length of long-span bridges in recent years, the main spans become longer, more flexible, sensitive, and prone to exhibit oscillations at low wind speeds, the influence of non-uniform flows on the vortex-induced vibrations (VIVs) of bridges should be considered. This study investigated the multi-mode VIVs of long-span bridges in both the completed bridge stage and erection stage using a taut-strip model under a uniform flow and two types of non-uniform flow. The non-uniform flows were generated by adjusting spires (both their separation distance and shapes) in wind tunnel. The two non-uniform flows were represented by the linear and parabolic wind velocity flow distributions. The characteristics of the vibration responses and wake flows and aerodynamic differences between different stages and under different incoming flows were discussed. The non-uniform flows disturb the regular vortices in the wake due to the variable wind velocity and higher turbulence intensity, leading to suppression of the VIV response. The multiple frequencies compete with each other and deplete their energy, and different frequency components distribute at different spanwise locations simultaneously.

Keywords: multi-mode VIV, taut-strip model, non-uniform flow

1. INTRODUCTION

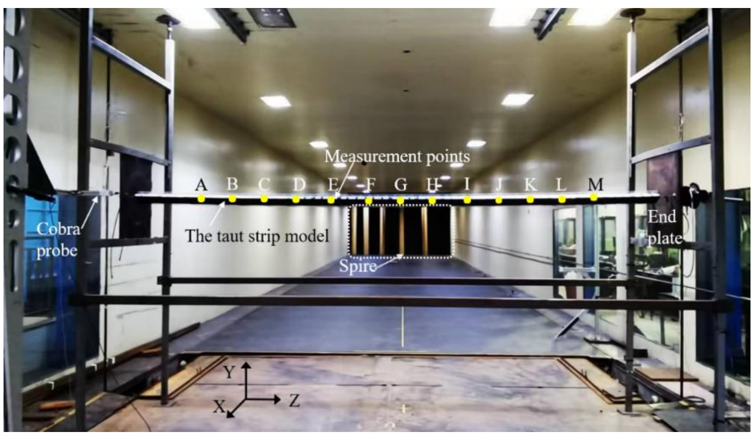
Owing to the flexibility and serried modes of long-span bridges, vertical VIVs of long-span bridges can be excited mode-by-mode when the wind speed increases gradually (Zhou et al., 2017). The incoming flow and turbulence intensity along the spanwise are not uniform in engineering (Li et al., 2011, 2014), and the existing VIV response investigations seldom consider the nonuniformity of the incoming flow. However, based on the full-scale measurements, the surrounding wind field is complex and inhomogeneous (Li et al., 2014) due to the variety of deep ravine terrain. A linear and a parabolic trend wind profile were observed in different inflow directions through the full-scale measurements (Lystad et al., 2018b). The multi-mode VIVs of flexible structures are prone to occur under these conditions mentioned above, these several modes compete with each other resulting in more complicated frequency components. Higher frequency components in lower modal VIVs may cause fatigue damage accumulation in the structure, which should be avoided (Li et al., 2018). Therefore, it is a challenge to predict the frequency patterns and other characteristics during VIV processes (Bao et al., 2021). For bridge structures, the characteristics, mechanism, and identification method of the multi-mode VIVs need further investigation.

2. EXPERIMENTAL SETUP

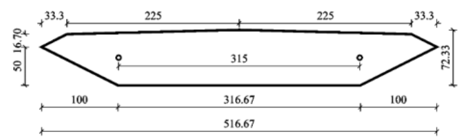
Wind tunnel experiments were performed at the Joint Laboratory of Wind Tunnel and Wave Flume (WTWF) at the Harbin Institute of Technology, P.R. China. In this study, the tested wind speed varied from 0.8 to 12 m/s at velocity intervals of 0.1 m/s.

2.1. Taut-strip model

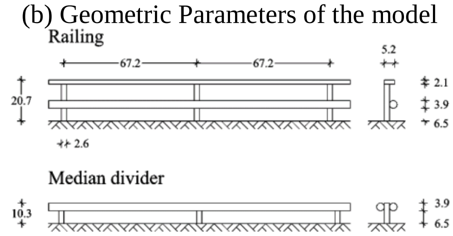
A taut-strip model of the Storebælt suspension bridge with a scale ratio of 1:60 was used in the wind tunnel tests, thirteen measurement points are shown in Fig. 1(a), denoted A to M. Six accelerometers were installed symmetrically at positions 1/2, 1/4, and 1/6 of the total length of the model. The length of the taut-strip model was 4000 mm, the aspect ratio of the whole model was 7.74, and the spanwise distance between each section model was 1 mm. The model mass was 3.65 kg/m, and the blockage ratio was 1.3%. The taut-strip model was composed of 20 sections, each section model was made of polystyrene foam plates covered with acrylonitrile butadiene styrene plastic plates to provide a lightweight section model with shape invariance. At a scale of 1:60, the width, height, and length of each section model were 516.67 mm, 72.33 mm, and 199 mm, respectively, as shown in Fig. 1(b). Railings and a median divider were installed on the upper surface along the span, as shown in Fig. 1(c), referring to Larsen et al. (2000). The first and second structural modal damping ratios were obtained through free vibration tests.



(a) Experiment setup of the taut-strip model



(b) Geometric Parameters of the model

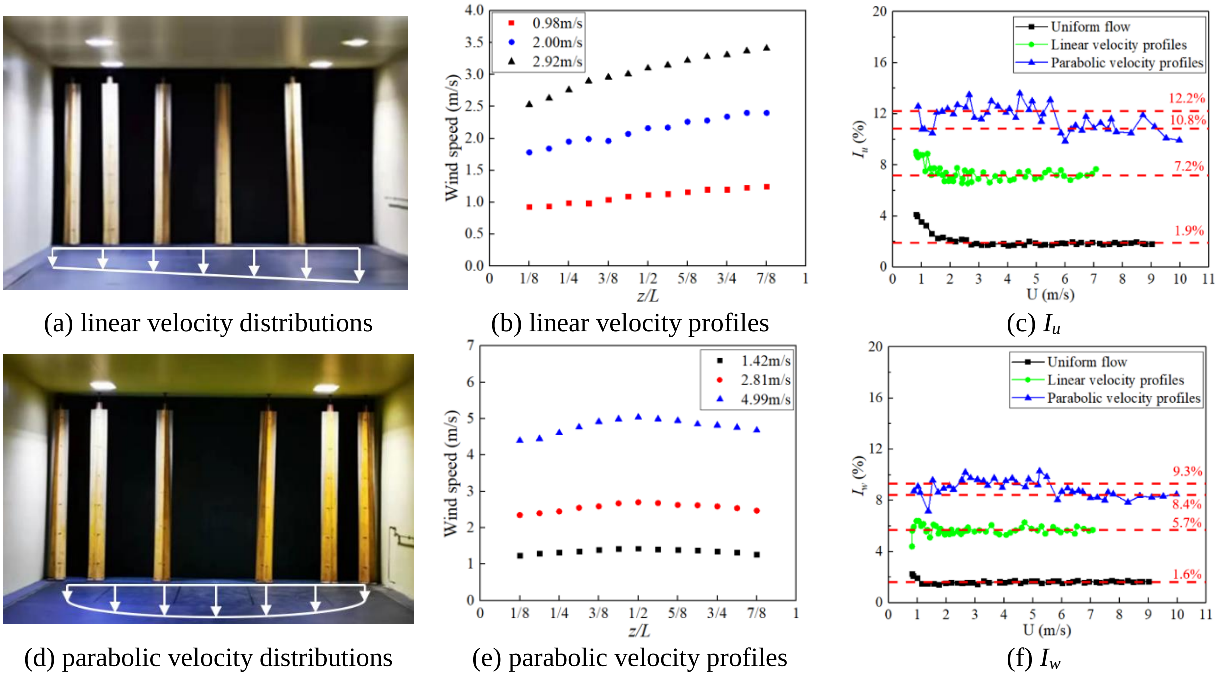


(c) Parameters of the railing and median divider

Figure 1. Experiment setup.

2.2. Non-uniform wind velocity profile

According to the full-scale measurements (Lystad et al., 2018b), the linear and parabolic wind velocity profiles were simplified as linear and symmetrical parabolic wind velocity profiles, respectively, as shown in Fig. 2(a) and (d). To obtain these wind velocity profiles, arrays of rectangular spires were arranged with different spacings in the wind tunnel. The velocity profiles of the two non-uniform flows are shown in Fig. 2(b) and (e), the trends of the measured wind velocity profiles are consistent with the trend of the designed profile. The higher the wind speeds of the incoming flows, the greater slope of the wind profiles. The average streamwise (I_u) and vertical (I_w) turbulence intensities vary with wind velocities at the midspan position are shown in Fig. 2(c) and (f).



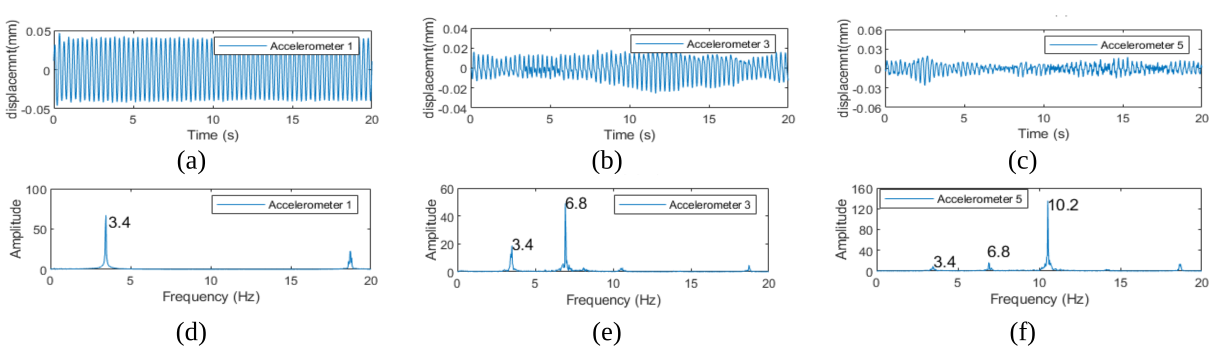
(a) linear velocity distributions (b) linear velocity profiles (c) I_u

(d) parabolic velocity distributions (e) parabolic velocity profiles (f) I_w

Figure 2. Arrangements of spires, measured velocity profiles, and turbulence intensities.

3. RESULTS AND DISCUSSIONS

To determine the VIV characteristics of each mode and understand the vibration mechanism of multi-mode VIVs, the maximum amplitudes of each modal VIV were extracted to investigate the responses based on time-history and frequency spectrum analyses. A typical case was selected: two obvious vibration frequencies (3.4 Hz and 6.8 Hz) and three frequencies (3.4 Hz, 6.8 Hz, and 10.2 Hz) are observed at Ur = 8.2 and 10.5 ($Ur=U/Hf$, f=3.4Hz), respectively, as shown in Fig. 3(e) and (f). Under the linear wind velocity profile, more than one frequency component was observed in the spectrum. These multiple frequencies compete with each other leading to unsteady vibration amplitudes during the sampling time.



(a) (b) (c)

(d) (e) (f)

Figure 3. Vibration responses of C1: (a), (d)Ur = 4.0; (b), (e)Ur = 8.2; (c), (f)Ur = 10.5

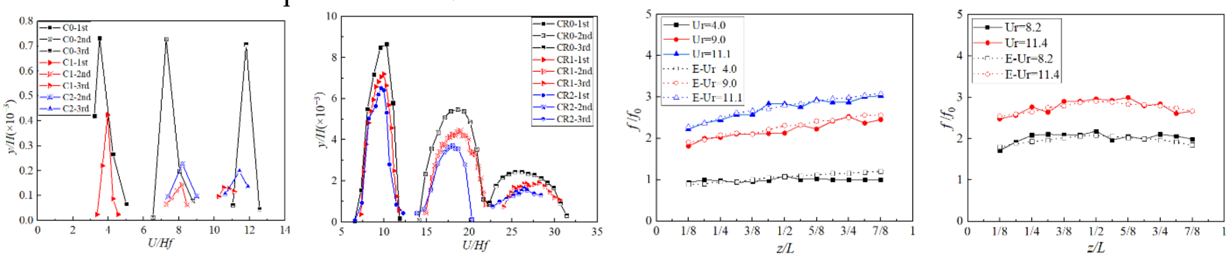
The vertical VIV responses of the taut-strip bridge without and with railings vary with reduced velocity are shown in Fig. 4(a) and (b) respectively, the 1st, 2nd, and 3rd structural mode vibrations appear successively with the increase in the reduced velocity. Compared with the uniform flow, an obvious reduction in the vertical VIV response is observed under linear and parabolic wind velocity profiles.

The vortex-shedding frequency of a flexible bridge model can be expressed as follows:

$$f(z) = \mathrm{St}\frac{U_0(z)}{H} \tag{1}$$

where $f(z)$ is the estimated vortex-shedding frequency along the span with the length of z, $U_0(z)$ is the incoming wind velocity along the span with the length of z, and H is the height of the taut-strip model; for the bridge without railings, St = 0.25.

Referring to Eq. (1), the estimated vortex-shedding frequency along the span direction can be predicted as illustrated in Fig. 4(c) and (d), where the solid and dashed lines represent the measured and estimated wake frequencies, respectively. The estimated vortex-shedding frequencies match the measured wake frequencies well.



(a) C0, C1, and C2 (b) CR0, CR1, and CR2 (c) C1 (d) C2

Figure 4. Measured and estimated vortex-shedding frequencies along the span under different wind speeds

4. CONCLUSION

In this study, the characteristics of multi-mode VIVs under non-uniform wind velocity profiles were investigated in the wind tunnel. A non-uniform wind velocity profile disturbs the regular vortices in the wake because of the variable wind velocity and higher turbulence intensity, leading to suppression of the VIV response evidently; the more frequency components are present, the smaller the amplitudes of the vibrations will be.

ACKNOWLEDGEMENTS

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