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High-mode Vortex-induced Vibration of Stay Cables: Field Measurements, Experiments and Aerodynamic Countermeasures

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SUMMARY:
With the increasing of main span of the cable-stayed bridges, the length of the longest stay cable has exceeded 600m， e. g., the longest stay cable length of Changzhou-Taizhou Yangtze River Bridge under construction in China is 633m. Therefore, the wind-induced vibration of super-long stay cables is one of the focused issues for wind-resistant design of long-span cable-stayed bridges. In this study, the field measurements, experiments and aerodynamic countermeasures of high-mode vortex-induced vibration of stay cables are presented. Taking Sutong Yangtze River Bridge (STB), the field measurements of the high-order vibration response of the stay cables were carried out. Then, the wind tunnel tests on VIV of the horizontal and inclined stay cable segment model with geometric scale ratio of 1:1 were carried out, respectively. Finally, the mode order amplification factor (MOAF) of the stay cable is proposed to design the flexible stay cable model for the prototype stay cable based on the similarity criteria for aero-elastic model design. Furthermore, the wind tunnel tests of the full aero-elastic model of the stay cable were carried out.

***Keywords:** stay cables, high-mode vortex-induced vibration, aerodynamic countermeasures*

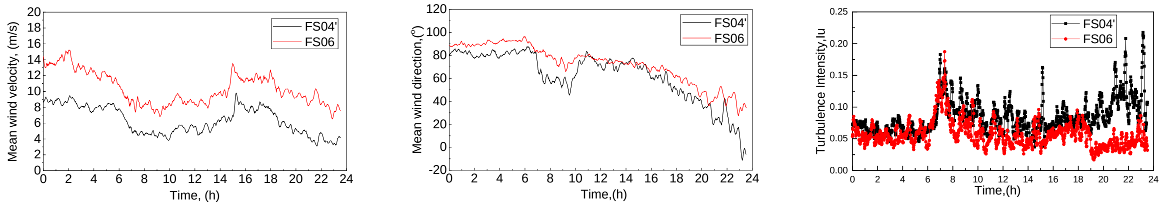
1. INTRODUCTION

In recent years, obvious high-mode VIVs of stay cables have been observed on some cable-stayed bridges under normal wind speed without precipitation (Susumu and Masahiro, 2014; Liu et al., 2021). Medium-amplitude vibration under wind without rain was observed on short indent stay cables of the Tatara Bridge in Japan (Susumu and Masahiro, 2014). The high-order wind-induced vibration phenomena were observed on JiaYu Yangtze River Bridge and STB (Liu, et al., 2021). Some scholars have conducted experimental research on the characteristics of the VIV of a stay cable under uniform or shear wind profiles (Zuo and Jones, 2009; Chen et al., 2015). Zuo and Jones (2009) conducted wind tunnel tests to investigate the effects of stay-cable inclination angles and wind direction on the wind-induced vibration of circular cylinders. Chen et al. (2015) studied the VIV characteristics of a 6.08-m-long stay cable under different wind profiles. However, there are few studies on high-mode VIV and aerodynamic VIV control measures for stay cables. Therefore, it is necessary to investigate the aerodynamic control measures of the high-mode VIV of stay cables to improve the service life of the stay cables and dampers.

2. FIELD MEASUREMENT

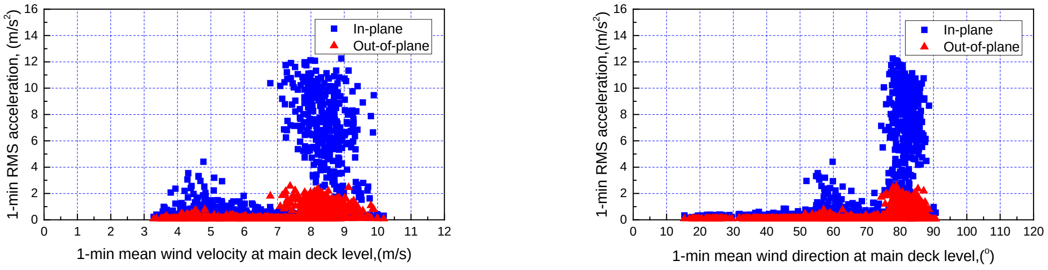
The structural health monitor system (SHMS) was installed on STB to monitor the natural environment and the corresponding bridge responses during construction and in-service stages. In order to further investigate the wind-induced vibration characteristics and mechanism of the stay cables, five two-axis accelerometers were installed on the five stay cables at 8.0 meters above the main deck, namely NA09U, NA18U, NA29U, NA30U and NA31U stay cables. The sampling frequency of the accelerometers is 100Hz, and the accelerometers range is ±2.0g.

The obvious wind-induced vibration responses of the stay-cables of STB were measured on August 15, 2018. The moving average wind velocity, direction and turbulence intensity with a time interval of 10 minutes and 1-min time step at main deck level are shown in Figure 1, respectively. As shown in Figure 1, the mean wind speed, direction turbulence intensity at main deck level in 0:00 to 6:00, August 15, 2018 are about 8.0 m/s, 80^o, and 0.05 to 0.07, respectively. However, considering that the bridge axis is 10^o from due north direction, the wind is actually perpendicular to the bridge axis. Moreover, the 1-min RMS acceleration responses of the stay cable NA30U with wind speed and direction at main deck level are given in Figure 2, respectively. As shown in Figure 2, the in-plane acceleration vibration responses are significantly larger than the out-of-plane acceleration vibration response of the stay cable, which are relatively large for wind speed is 7.0 to 10 m/s and wind perpendicular to the bridge axis.



(a) (b) (c)

Figure 1. Time histories of wind velocity, wind direction and turbulence intensity at mid-span deck level and south pylon top of STB, (a) Wind velocity; (b) Wind direction; (c) Turbulence intensity along wind direction.



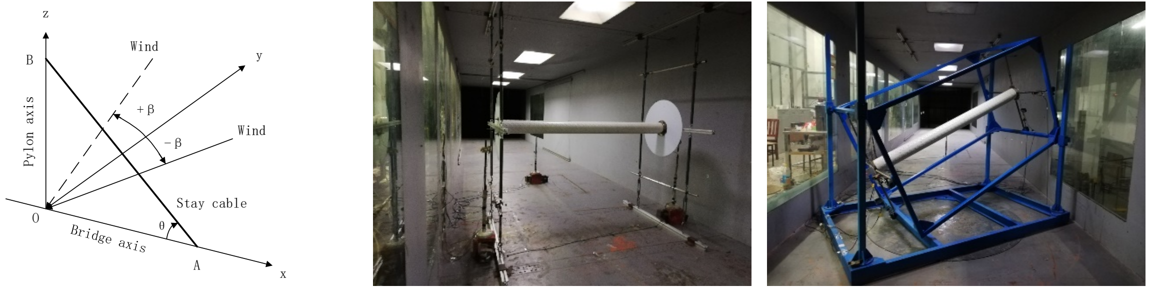
(a) **(b)**

Figure 2. 1-min RMS of acceleration responses of NA30U stay-cable vs. wind speed and wind direction. (a) 1-min RMS acceleration vs. wind velocity; (b) 1-min RMS acceleration vs. wind direction.

3. STAY CABLE MODEL AND EXPERIMENTAL RESULTS

3.1 Section model of stay cable

To eliminate the effects of the Reynolds number on the VIV response, a dimpled stay cable section model was designed according to the prototype stay cable of STB, and the corresponding geometry scale of the stay cable section model is $\lambda_{\mathrm{L}} = 1:1$. In order to study the VIV characteristics and aerodynamic countermeasures, the wind tunnel tests of the horizontal stay cable model are carried out firstly. Then, the experiments of inclined stay cable model are conducted for inclination angles of 25^{o}, 40^{o}, and wind yaw angle of −60° to 60° with an interval of 15°. Figure 3 shows the wind yaw angle and inclination angle of the stay cable, horizontal and inclined stay cable section model, respectively.



(a) (b) (c)

Figure 3. Wind yaw angle, inclination angle and pictures of stay cable section model, (a) wind yaw angle and inclination angle, (b) horizontal stay cable section model, and (c) inclined stay cable section model.

3.2 Flexible stay cable model

In order to balance the relationship between the geometry scale and Reynolds number effects on high-model VIV of the flexible stay cable model, a novel method is proposed to design the flexible stay cable model. Firstly, according to the similarity criterion of the aero-elastic model, the length scale ratio of FASM of NJ32D stay cable of STB is determined as $\lambda_{L1} = 1/5$. Secondly, the mode order amplification factor (MOAF), n_f, of the stay cable is proposed to consider the high-mode wind-induced vibration of the stay cable. Here, the value of n_f is 3.3. The force of the SASM should satisfy the following relationship,

$$T_{ms} = \lambda_{L2}^{2} \cdot n_f^{2} \cdot T_m \tag{1}$$

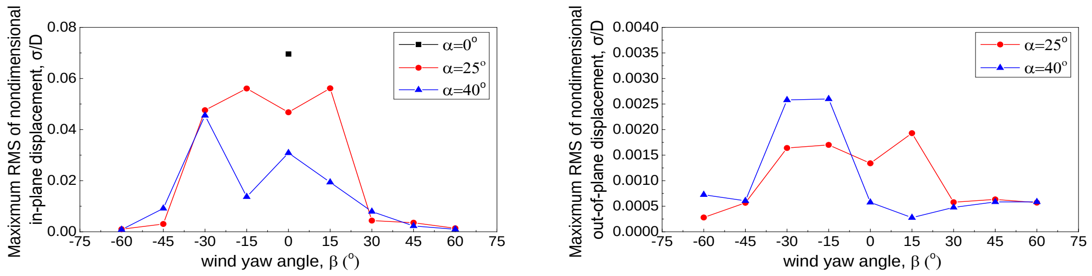
where, T_m, and T_{ms} are the force of the full aero-elastic stay cable model(FASM) and SASM, respectively. It should be noted that the fundamental frequency of the SASM of the stay cable is n_f times that of the FASM. Therefore, the SASM can only reflect the high-order vibration response characteristics of the stay cable with an interval of n_f times frequency.

3.3 Experimental results

Figure 4 shows the maximum RMS in-plane and out-of-plane displacements of the stay cable section model with different inclination angles vs. wind yaw angle. As shown in Figure 4, the in-plane vibration response of the stay cable is much larger than the out-of-plane vibration response, and the maximum RMS displacements of the horizontal-cable model are larger than those of the cable model when the inclination angles are 25° and 40°. However, there is no clear change rule for the out-of-plane VIV response of the stay cable. Figure 5 shows the RMS of acceleration at P_{A1} of the flexible stay cable model with/without helical fillets for wind yaw angle of $\beta = 0^{\circ}$ vs. the reduced wind velocity.

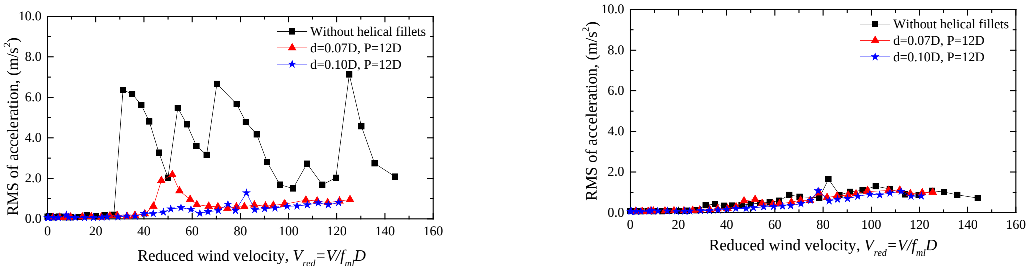
4. CONCLUSIONS

The main conclusions can be drawn as follows: (1) The obvious high-mode VIV responses with low amplitude are observed on stay cables of STB under 7.0 to10.0m/s wind speed without precipitation. (2) The stay cable exhibits a significant VIV phenomenon under perpendicular wind or wind yaw angle of 0°, 15°, –15°, and −30°. (3) The MOAF of the stay cable is proposed to design the flexible stay cable model for the prototype stay cable. (4) The VIV responses of the stay cable can be effectively suppressed with the circular double helical fillets of diameter of d=0.10D and pitch of P=12D.



(a) (b)

Figure 4. Maximum RMS of non-dimensional in-plane and out-of-plane displacements of the stay-cable model without helical wires vs. wind yaw angle: (a) in-plane displacements and (b) out-of-plane displacements



(a) (b)

Figure 5. RMS of acceleration at P_{A1} of the flexible stay cable model for wind yaw angle of $\beta = 0^\circ$ vs. the reduced wind velocity, (a) in-plane vibration, and (b) out-of-plane vibration.

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