13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-183

Field monitoring and mitigation for high-mode vortex-induced vibrations of cables in cable-stayed bridges

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ABSTRACT: With the increase in the span of cable-stayed bridges, stay cables tend to become more flexible and longer, which leads to lower damping and structural natural frequency. Therefore, it is more vulnerable to wind load effects. This study aims to investigate the characteristics and mechanisms of vortex-induced vibrations (VIVs) of stay cables based on long-term field monitoring for a sea-crossing cable-stayed bridge. First, a vibration monitoring system with a high sampling frequency for cables was established. On this basis, the time history data of vibration acceleration for cables with different lengths were collected to study the vibration characteristics, such as vibration amplitudes and frequency distributions of cables. For the longer stay cables, the cable vibrations with over-limit acceleration amplitudes were observed in a wind velocity region of 6~9m/s with very high vibration frequencies, and the wind directions that caused the vibrations were almost vertical to the stay cables. The mechanism of cable vibrations was discussed and investigated based on the relationship between wind characteristics parameters and the vibration response of cables. VIV occurred because the control frequencies of the cable vibrations coincided with the high-mode vortex shedding frequencies of the cables. Finally, the effects of different types of dampers on suppressing VIV were compared and investigated.
KEY WORDS: Cable-stayed bridge; cable vibration; bridge health monitoring; vortex-induced vibration.

1 INTRODUCTION

In the past few decades, cables have been widely used in long-span bridges. The cables of bridges tend to be more flexible, longer, and prone to vibrate due to low damping and structural natural frequency. The wind-induced vibration of stay cable can be roughly categorized as rain-wind-induced vibrations (RWIV), vortex-induced vibrations (VIV), and dry galloping (DG) classified by different vibration mechanisms and characteristics.

VIV of cables is a common form of cable aerodynamic instability phenomena with limited vibration amplitudes. When flow passes around cables, vortices are generated along the profiles of cylinder cables, alternatively on the upper and lower sides, and induce forces perpendicular to the wind direction[1]. As the length of stay cables grows, the structural natural frequency tends to be much smaller, indicating a much lower critical wind velocity corresponding to the classical vortex shedding. For a long cable, a high-mode VIV can be easily excited even under a moderate wind speed.

Field monitoring is meaningful for investigating the vibration characteristics of cables. Based on continuous half-year data from the bridge structural health monitoring system (SHMS), Ge found the frequency of the in-plane VIV is around 9.6 Hz for a 577m cable, and then validated that the cable is mainly subjected to high-frequency VIV[2]. Matsumoto conducted a field observation for a cable model of the Meiko West Bridge and discovered rain-wind-induced vibrations by comparing the vibration characteristics under different weather conditions [3]. Cable vibrations of the Fred Hartman Bridge were also investigated and studied by field monitoring. RWIV requires a much higher reduced velocity than that required by VIV[4], and the high-order modes play the dominant role in the VIV of cables[5].

The vibrations of cables may cause fatigue or service problems if the vibration amplitudes are not mitigated by dampers or other countermeasures[6]. Therefore, aerodynamic and damping countermeasures were employed to mitigate cable vibrations. To optimize the aerodynamic profile of cables, the effects of helical strakes on suppressing VIV are studied by field measurements [7] and wind tunnel tests [8]. In addition, various types of dampers are usually installed near the anchor end of the cables to mitigate cable vibrations, including oil dampers, high-damping rubber dampers, viscous shear dampers [9], Magnetorheological (MR) dampers [10] and eddy current dampers [11]. The mitigation theories of various types of dampers for suppressing cable vibrations are different. Furthermore, it is still lacking an in-depth study regarding the effects of dampers on suppressing cable vibrations based on the field observation data of the bridge SHMS.

In this study, field monitoring was conducted on a cable-stayed bridge. The time history data of vibration acceleration for cables were collected to study the vibration characteristics and mechanism. Various types of dampers are adopted on symmetrical cables to compare the effects of different dampers on suppressing cable vibrations.

2 VIBRATION MONITORING SYSTEM FOR CABLES

The field monitoring was conducted on a cable-stayed bridge (Figure 1) located in Zhoushan of Zhejiang Province in China. As part of an important cross-sea passage, the Ningbo-Zhoushan Expressway between the island and the mainland,

DOI: 10.3217/978-3-99161-057-1-183

this bridge is a cable-stayed bridge with twin towers and a semi-floating system, and the main span of this bridge is 580m. The height of the bridge tower is 151m. The bridge girder is supported by a total of 168 stay cables, and the length of the cables is 63-298m.

Figure 1. Bridge for field monitoring.

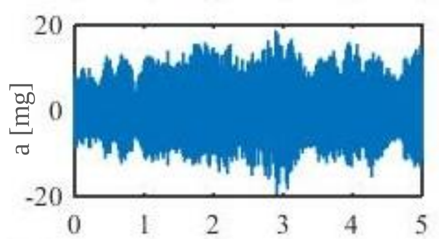
In the construction stage of the bridge, viscous shear dampers were pre-installed near the anchor of every cable of the bridge. However, on sunny and no precipitation days, obvious cable vibrations can still be found on this bridge. The cable monitoring system, as an important part of the SHMS, is shown in Figure 4. In total, 52 groups of acceleration sensors were installed on the cables at a height of 5m. To analyze the vibration characteristics of cables, the time history monitoring data of cable acceleration sensors and wind speed sensors were analyzed.

3 DYNAMIC CHARACTERISTICS OF CABLE VIBRATIONS

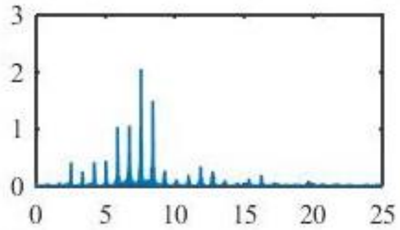
3.1 Vibration characteristics of cables with different lengths

According to a 5-day period of monitoring data for cables, the dynamic characteristics of different cables were investigated and compared. In this study, cables are roughly categorized based on their lengths: short cables (<100m), medium-length cables (100~200m), and long cables(>200m).

For the short cables, the vibration amplitude is quite small (Figure 2(a)). Based on the power spectral density (PSD) of acceleration, the vibration frequencies are mainly between 5-10 Hz, which is quite average and not concentrated on one or several typical frequencies (Figure 2(b)).



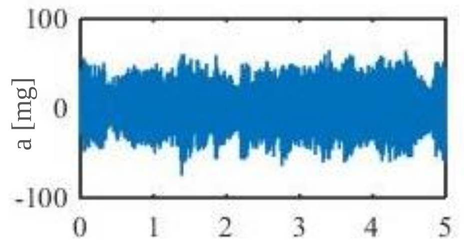
(a) Time history data of acceleration.



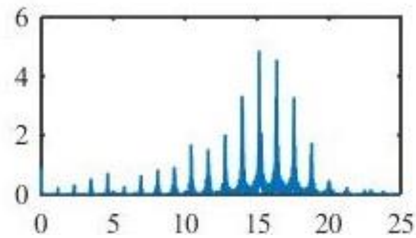
(b) Acceleration PSD.

Figure 2. Vibration data and frequency distributions of a short cable.

According to Figure 3(a), for the medium cables, the vibration amplitude is larger than short cables but still smaller than the warning value defined in “Technical specifications for structural monitoring of highway bridges” (JT/T 1037-2022) [12]. The vibration frequencies are mainly between 5~20 Hz, which is quite average and not concentrated on one or several typical frequencies (Figure 3(b)).



(a) Time history data of acceleration.



(b) Acceleration PSD.

Figure 3. Vibration data and frequency distributions of a medium cable.

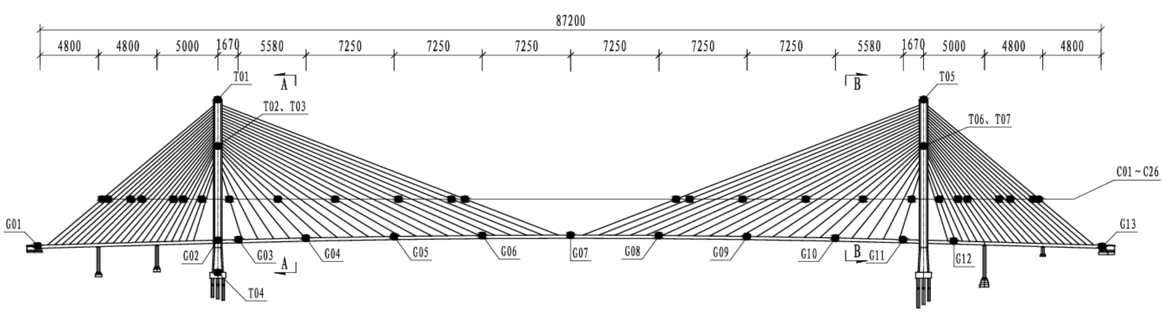
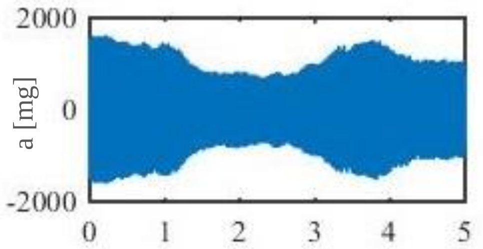


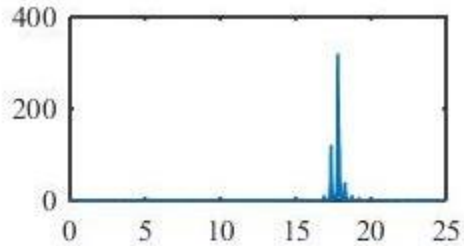
Figure 4. Cable monitoring system of the bridge.

DOI: 10.3217/978-3-99161-057-1-183

For the long cables, abnormal vibrations are excited (Figure 5(a)). During the vibration period, the vibration amplitude is quite large, and the energy is mainly concentrated in the high-frequency region (Figure 5(b)).



(a) Time history data of acceleration.



(b) Acceleration PSD.

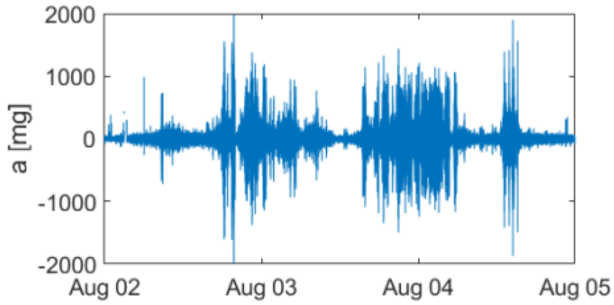
Figure 5. Vibration data and frequency distributions of a long cable.

Therefore, the length of the cables is a crucial parameter that determines whether abnormal vibrations will be excited or not. This is because long cables with lower structural natural vibration frequencies and damping are more vulnerable to the wind effects and are more easily excited into large amplitude vibrations.

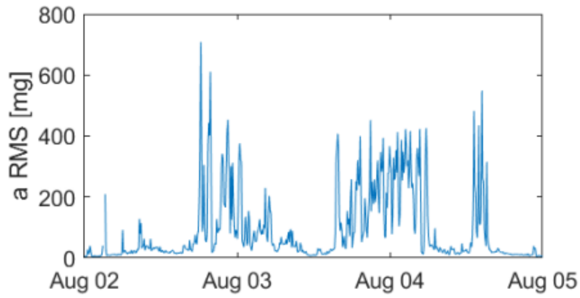
3.2 Vibrations of long cables and mechanism analysis

A typical large amplitude vibration event of a long cable is analyzed to further analyze the vibration characteristics of long cables.

As shown in Figure 6(a), a continuous cable vibration event in the period of August 2nd and 5th was recorded by the cable vibration acceleration sensors. The root-mean-square (RMS) values of every ten-minute acceleration are calculated (Figure 6(b)), and the maximum value is 723 mg, which is far greater than the allowable limit for cable vibrations defined in "Technical specifications for structural monitoring of highway bridges" (JT/T 1037-2022) [12].



(a) Time history data.



(b) RMS value.

Figure 6. Time history data and RMS value of acceleration.

Figure 7 shows the average power spectral density calculated using every 10-minute acceleration. The vibration was found to be concentrated in high-frequency regions, and the main frequency of vibration is 17.9 Hz.

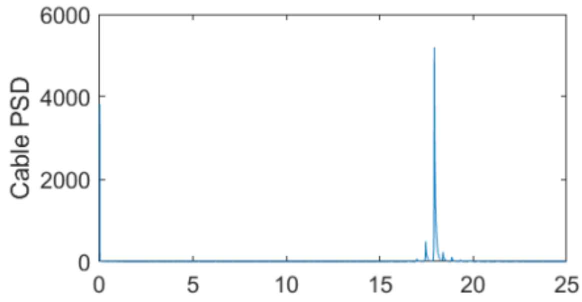
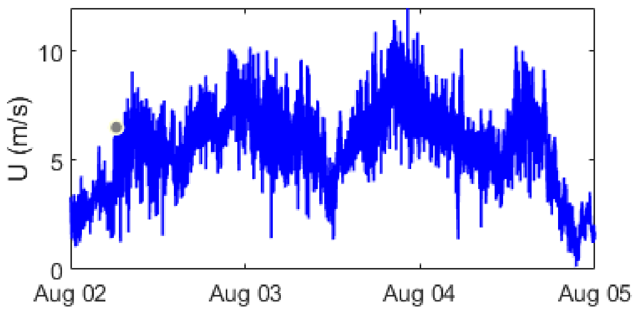
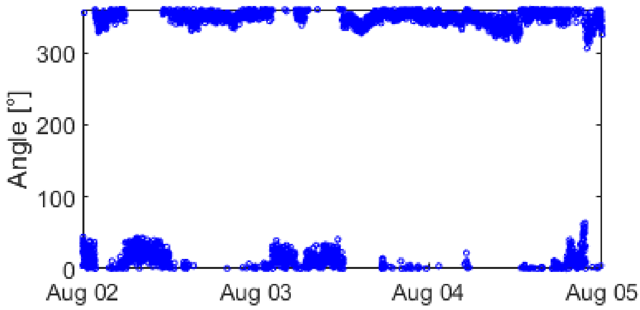


Figure 7. Acceleration PSD.

To analyze the vibration mechanism, the relationship between the vibration amplitude and wind characteristics was studied. The wind velocity and wind angle in this period are recorded by the wind speed sensors (Figure 8). Therefore, it can be inferred that the cable vibration may be excited under nearly north-south wind conditions.



(a) Wind speed.



(b) Wind angle.

Figure 8. Time history data of wind.

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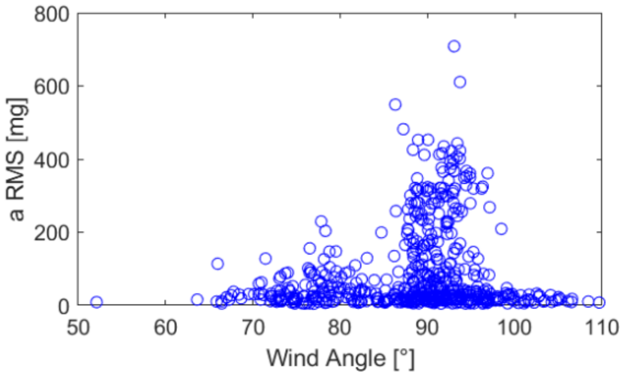
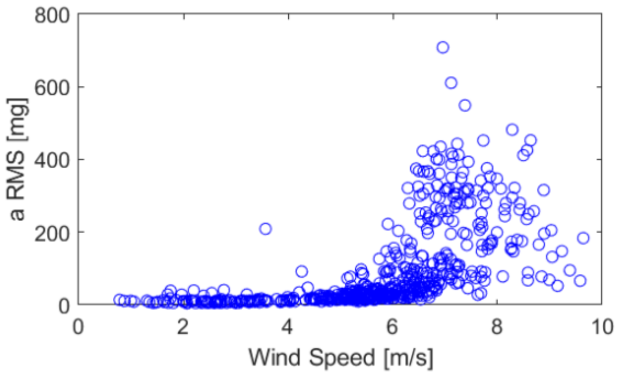
Considering the installation direction of the bridge wind speed sensors as well as the angle between the stay cable and pylon, the wind yaw angle between the stay cable and wind was recalculated. The relationship between the acceleration vibration amplitudes and wind angles is shown in Figure 9(a). Large vibration amplitudes occur when the wind angle is around 90°, which means the wind direction is vertical to the cable plane. In addition, the wind speed vertical to the cable plane was also calculated (Figure 9(b)). It can be concluded that vibrations are maximized at a wind velocity of 6 to 9 m/s.



(a) Acceleration response under different wind yaw angles.



(b) Acceleration response under different vertical wind speeds.
Figure 9. Relationships between acceleration responses and wind characteristics.

For the VIV of cables, when the flow passes around the section of stay cables, vortex shedding emerges on the upper surface and lower surface alternatively, and the frequency of vortex shedding f_v can be defined as equation (1) [13]

$$f_v = \frac{US_t}{D} \quad (1)$$

Where U is the average wind speed. S_t is the Strouhal number, which is related to the section configuration, for a circle section, $S_t = 0.2$. D is the diameter of the cable. When vortex shedding frequencies of cables are close to the structural natural frequencies, cables will be excited into VIV resonance.

The vibration frequencies are calculated to investigate the vibration mechanism. In Figure 10, the x-axis represents the wind speeds, and the y-axis represents one-minute vibration frequencies. The maximum frequency calculated by the PSD of acceleration is selected as the main frequency of cables in one minute. Therefore, the scatters indicate different main vibration frequencies of cables under different wind conditions.

However, as the height increases, the wind speed apparently increases. Therefore, considering the overall speed of the wind profile passing around cables, the height of the cable and the wind field landform, the wind speed measured on the bridge deck should be multiplied by a factor of 1.3. Based on the dimensions of stay cables, the fundamental frequencies of vortex shedding can be calculated. Therefore, the relationships between different orders of vortex shedding frequencies and bridge wind speeds can be drawn as a red line (Figure 10). For the long cables, the micro-vibrations are mainly concentrated in the frequency range of 17~20 Hz, and 2~5 Hz (Marked as circles). The micro-vibrations are mainly catalogued into the vehicle-bridge coupled vibration and the vehicle load. Except for these scatters. The main distribution of scatters coincides with the line, especially in the wind speed region of 6~9 m/s, which indicates that the vibration frequencies are consistent with various modes of vortex shedding frequencies, and thus proves that the vibrations of the cable are dominated by VIV.

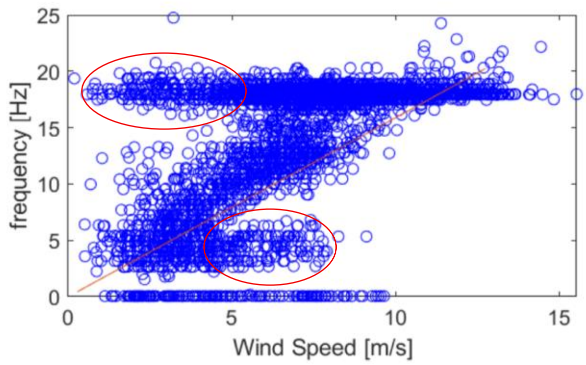


Figure 10. Relationship between vibration frequencies and vortex shedding frequencies of cables.

4 MITIGATION OF CABLE VIBRATIONS

Different dampers are utilized to compare their effects in mitigating the cable vibrations. The damping ratios are set to achieve the optimal dimensionless damping coefficient 1.5~2.0 for different cables to minimize the large vibrations under lower frequencies. According to previous monitoring history data, under a certain wind field condition, the VIV responses of the cables symmetric along the bridge axis are quite similar because the structural parameters and natural frequencies of cables are almost the same. Therefore, different dampers are adopted for the symmetric long cable groups to investigate their effects on suppressing VIV. An eddy current damper (Figure 11(a)) is mounted on the cable R-20, and an MR damper (Figure 11(b)) is mounted on the cable R-21, respectively. For the sake of comparison, the new viscous shear dampers (Figure 11(c)) are employed on the symmetric cables L-20 and L-21. The parameters of dampers are designed with the consideration of the suppression of low-mode rain-wind vibrations.

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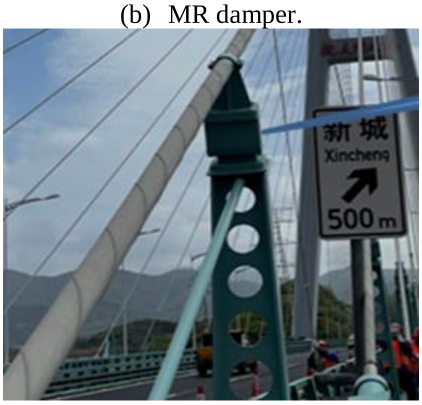
(a) Eddy current damper.

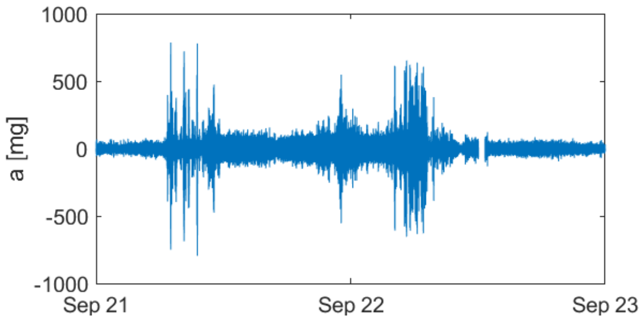

(b) MR damper.



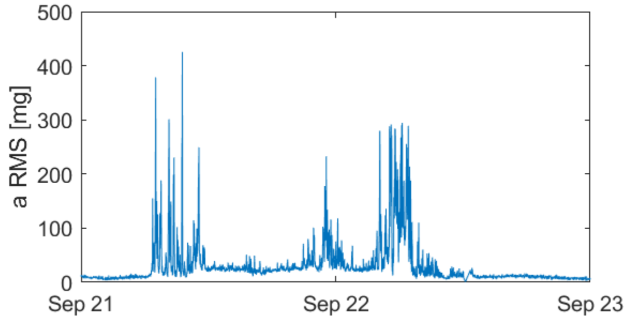
(c) Viscous shear damper.

Figure 11. Three types of dampers on cables.

Because the excitation of cable vibration under high frequencies (f >15Hz) is quite difficult, field monitoring is conducted under the condition of the ambient excitation of natural wind. A typical VIV response occurred in September of 2024 after the replacement of dampers was selected to study the effects of dampers on suppressing VIV. By comparing the time history data and RMS value of acceleration for the symmetric cables of R-20 (Figure 12) and L-20 (Figure 13), the VIV response of cable R-20 is significantly larger than that of L-20, which proved that the viscous shear damper is more effective in suppressing the high-mode VIV than the current eddy damper. When the high-mode (30^{th}-40^{th}) VIV of cables occurs, the position of the damper is close to the stagnation point of vibrations, and thus, it needs a large damping coefficient to suppress vibrations [14]. However, for the current eddy damper, as the vibration frequencies increase, the equivalent damping coefficients decrease [15], which is disadvantageous to the suppression of a high-mode VIV.

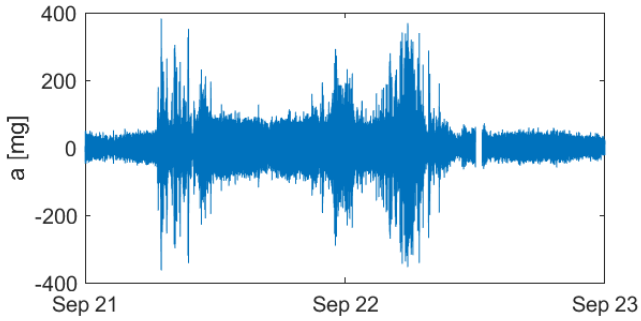


(a) Time history data of acceleration.

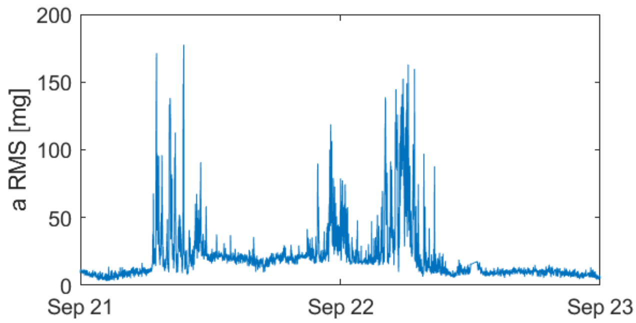


(b) RMS value of acceleration.

Figure 12. Vibration data of Cable R-20.



(a) Time history data of acceleration.



(b) RMS value of acceleration.

Figure 13. Vibration data of Cable L-20.

By comparing the time history data and RMS value of acceleration for the symmetric cables R-19 (Figure 14) and L-19 (Figure 15), the VIV amplitude of cable R-19 is a little smaller than that of L-19, which proved that the MR damper is slightly better than the viscous shear damper in suppressing the high-mode VIV. The initial stiffness of the MR damper may provide additional damping effects [16].

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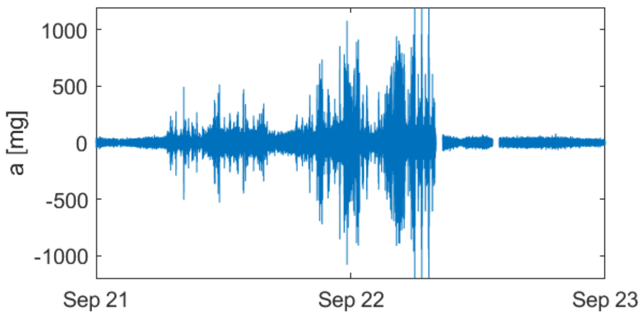
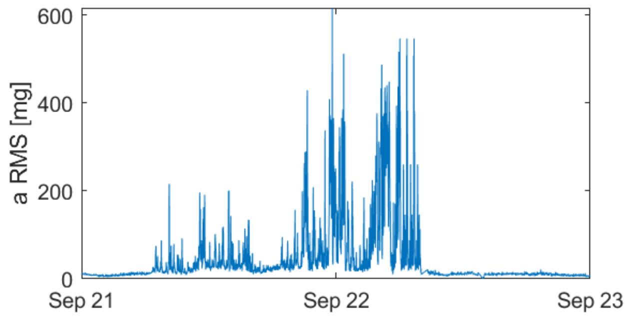
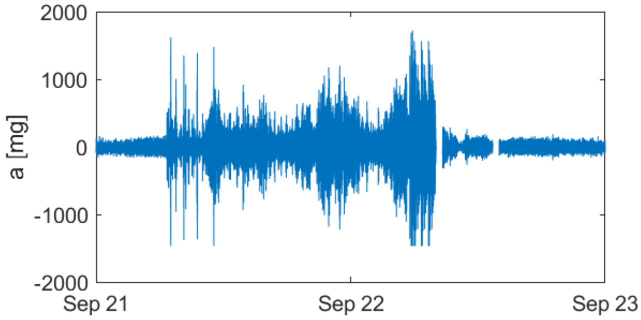


(a) Time history data of acceleration.

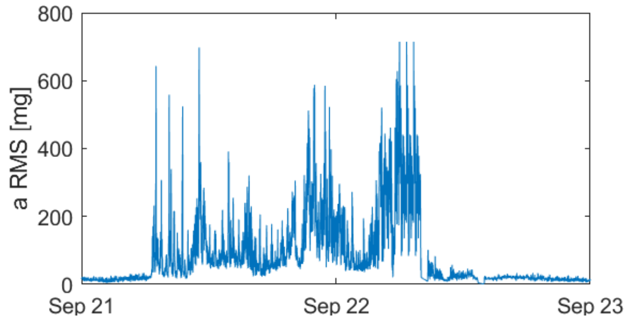


(b) RMS value of acceleration.

Figure 14. Vibration data of Cable R-19.



(a) Time history data of acceleration.



(b) RMS value of acceleration.

Figure 15. Vibration data of Cable L-19.

However, for these three types of dampers, the high-mode VIV cannot be entirely suppressed. Because the high-mode vibration may have multiple stagnation points along the cables, the installation positions of dampers tend to be close to the stagnation points. Therefore, stock-bridge dampers should be installed at suitable positions of cables as complementary dampers to mitigate the specific high-mode VIV [14].

5 CONCLUSIONS

In this study, continuous field monitoring is conducted to investigate the vibration characteristics of stay cables for a cross-sea cable-stayed bridge. Different dampers are mounted to compare their effect on suppressing vibrations. The conclusions are as follows:

(1) According to the field monitoring data, the long cables of this long-span bridge are easily excited into a high-mode vibration under the vertical wind in a speed region of 6-9m/s.

(2) For the high-mode vibrations of long cables, the vibration frequencies of cables under different wind speeds are consistent with various modes of vortex shedding frequencies, proving that the vibrations of the cable are dominated by VIV.

(3) For the mitigation effects of high-mode VIV of cables, MR damper>viscous shear damper>current eddy damper. However, the effects of the three types of dampers on controlling high-mode VIV are limited. Stockbridge dampers should be designed to mitigate the specific high-mode vibration.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Independent Research and Development Projects of Zhejiang Scientific Research Institute of Transport (ZK202401, ZK202405, ZK202501).

REFERENCES

[1] M. Virlogeux, State-of-the-art in cable vibrations of cable-stayed bridges. Bridge Structures, 1(3): 133–168, 2005.

[2] C. Ge and A. Chen. Vibration characteristics identification of ultra-long cables of a cable-stayed bridge in normal operation based on half-year monitoring data. Structure and Infrastructure Engineering, 15(12): 1567–1582, 2019.

[3] M. Matsumoto, H. Shirato, T. Yagi, et al. Field observation of the full-scale wind-induced cable vibration. Journal of Wind Engineering and Industrial Aerodynamics, 91(1–2): 13–26, 2003.

[4] D. Zuo, N. P. Jones, and J. A. Main. Field observation of vortex- and rain-wind-induced stay-cable vibrations in a three-dimensional environment. Journal of Wind Engineering and Industrial Aerodynamics, 96(6–7): 1124–1133, 2008.

[5] J.A. Main, N. P. Jones, Full-scale measurements of stay cable vibration. In: Proceedings of the Structures Congress, Philadelphia, Pennsylvania, 2000.

[6] Z. Liu, Z. Zhu, C. Wei, et al. Observation of vortex-induced vibration and wind characteristics of cables across the Yangtze river bridge. Journal of Railway Science, 17, 2020.

[7] J.K. Vandiver, S. Swithenbank, V. Jaiswal, et al. The effectiveness of helical strakes in the suppression of high-mode-number VIV. In: Offshore Technology Conference, Houston, Texas, U.S.A., 2006.

[8] T. Zhou, S. Razali, Z. Hao, et al. On the study of vortex-induced vibration of cylinder with helical strakes. Journal of Fluids Structure, 27, 903–917, 2011.

[9] L. Sun, H. Zhou, A, Chen. Classification and performance of vibration control device for cables of long span cable-stayed bridge. Journal of World Bridge, 4:36-40, 2001.

[10] P. Zhou, M. Liu, W. Kong, et al. Modeling and evaluation of magnetorheological dampers with fluid leakage for cable vibration control. Journal of Bridge Engineering, 26(2):04020119, 2021.

[11] X. Lei, H. Niu, Z. Chen, et al. Development and Application of a New-type Eddy Current TMD for vibration control of Hangers of Long-span Steel Arch Bridges. China Journal of Highway and Transport, 28(4), 2015.

DOI: 10.3217/978-3-99161-057-1-183

[12] Ministry of Transport of the People's Republic of China. Technical specifications for structural monitoring of highway bridges: JT/T 1037-2022, 2022.
[13] Z. Chen. Bridge wind engineering. China Communications Press, Beijing, China. 2005.
[14] C. Yang. Theoretical and experimental studies on higher multi-mode vibration control of cables. PhD thesis, Hunan University. 2022.
[15] Z. Wang, Z. Cheng, H. Wang, et al. Eddy-current inertial mass damper for cable vibration control. China Civil Engineering Journal, 12 (54): 53-63, 2021.
[16] M. Wang, F. Wang, R. Zhao, et at. Application Research of Passive Magnetorheological Dampers for Vibration Suppression of Stay Cables in Real Bridges. Journal of North China University of Water Resources and Electric Power (Natural Science Edition) 11, 2024.