Girder-tower connected viscous damper solution for multi-mode vortex-induced vibration control of long-span suspension bridges

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SUMMARY:
Vertical vortex-induced vibrations have been observed on several long-span suspension bridges, where several vertical modes of stiffening girder are excited individually in different wind velocities. This paper proposed a girder-tower connected viscous damper solution to solve the multi-mode vertical vortex-induced vibration problem of long-span suspension bridges. The minimal modal damping ratio of multiple modes sensitive to vortex-induced vibrations was used to evaluate the performance of the damper system, for which the complex modal analysis with a ternary search algorithm was adopted to find the multi-mode optimal damper parameter. Taking the Yingwuzhou Yangtze River Suspension Bridge as an example, four torsional eddy current dampers have been installed with the optimized parameters calculated by this paper. it is found that the structural damping ratio increased by three times after the installation of the girder-tower viscous damper, and the vortex-induced vibrations can be significantly suppressed and meets the requirement of the Chinese Wind-resistant Design Specification for Highway Bridges.

Keywords: long-span suspension bridges, vortex-induced vibration, multi-mode control

1. INTRODUCTION

Nowadays, the development of the traffic network requires bridges across wider rivers and valleys. Long spans reduce the stiffness of the bridge, making it susceptible to wind-induced vibrations. The aerodynamic stability becomes a shortcoming of long-span bridges. Vortex-induced vibration (VIV) is a type of wind-induced vibration that occurs in the smooth wind flow. Owing to its resonance characteristic, several vertical modes of stiffening girder are excited in turn with increasing of wind velocity. The long-term monitoring data revealed that the Xihoumen Bridge suffered multiple VIV with different modes (Li et al., 2014). Chen (2013) proposed a novel multi-supported aeroelastic model to study the characteristic of the higher mode VIV and pointed out that the higher mode VIV is more harmful to bridges due to its lower structural damping and higher vibration acceleration.

Current VIV control methods encounter difficulties in controlling multi-mode VIV of long-span bridges. The flutter stability requires priority assurance in the current design concept, which narrows the options for applying aerodynamic methods to the VIV control. Excessive additional mass also makes it difficult to use multiple TMDs to control multi-mode vibrations. Referring to the application of the viscous dampers in the multi-mode control of cables, this paper hence proposed a girder-tower connected viscous dampers solution for multi-mode VIV control of long-span bridges. The solution is suitable for VIV control of almost all suspension bridges without the additional mass.

2. CONSTRUCTION OF THE GIRDER-TOWER CONNECTED DAMPERS

It is well known that discrete arranged viscous dampers installed in a location near the support of a beam or a cable can supply additional damping ratio to the structure (Krenk et. al. (2005)). So it is interesting to investigate the damping effect of the discrete viscous dampers connecting the bridge girder and the bridge tower of a suspension bridge. For a floating suspension bridge, the relative displacement is always exisit between the girder and tower for various modes, so it is a good choice to install a damper directly at the intersection of the girder and tower, as shown in Figure 1(a). However, there is no relative displacement at the intersection of the girder and tower for a simply-supported bridge. Therefore, a damper installed away from the support through a rigid corbel can be employed as shown in Figure 1(b), in which the relative displacement can be ensured.

The realization of the vertical damper should be taken carefuly to release the additional forces and moments of the horizontal vibration, especially for the seismic vibration. A connecting rods system can be utilized to achieve this goal. As shown in Figure 1(c), it translates the girder's vertical displacement and releases the torsional and horizontal constrains when the contacted angle θ is small. The translated vertical displacement can be dissipated by a torsional eddy current damper.

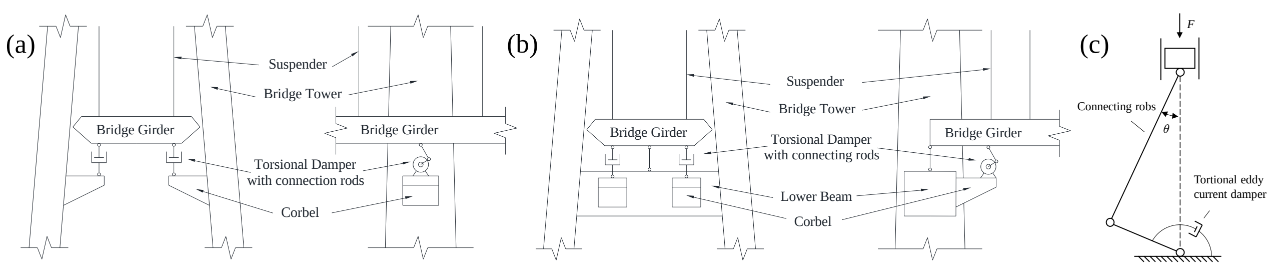

Figure 1. Schematic of the damper arrangement of (a) the floating suspension bridge and (b) the simply-supported suspension bridge, and (c) the damper-robs system schematic

3. PARAMETERS OPTIMIZATION

Benefit from the unimodal characteristic of the additional damping ratio provided by a damper, the optimal objective of the damper can be set to maximize the minimum additional damping ratio ζ_r of the selected modes, that is:

$$maximize\{\min\{\zeta_1, \zeta_2 \ldots \zeta_n\}\} \tag{1}$$

It is obvious that the minimum function maintains the unimodal characteristics when the derivatives of all the functions are strictly monotonic.It is generally very difficult to obtain an analytical solution of Eq.(1). Ternary search is used in this study to find the peak value of such a unimodal function. Ternary search is an iterative algorithm, which usually works as following: It starts with a limited open interval (l, r), then takes two points (a, and b) to divide the interval into three parts. Then, through a comparion of the function values at *a* and *b*, the interval can be reduced to the two sub-intervals around the maximum and it moves to the next iteration until the prescribed relative accuracy is reached. The golden ratio, $(\sqrt{5}-1)/2$, is used to divide the interval, which has been proved to provide the best performance of the ternary search algorithm (Kiefer, 1953), because the function value can be reused in the next iteration.

4. CASE STUDY OF THE YINGWUZHOU YANGTZE RIVER BRIDGE

The Yingwuzhou Yangtze River Bridge is located on the Yangtze River in Wuhan, Hubei, China. It is a suspension bridge with three towers, 200+850+850+200 m spans distribution. It is reproted that it experienced a high-mode vertical VIV on April 26, 2020, which cause driving discomfort and arouse public attention. To sovle this problem, four torsional eddy current dampers were installed on the two sides of the middle tower to control the high-mode VIV as shown in Figure 2.

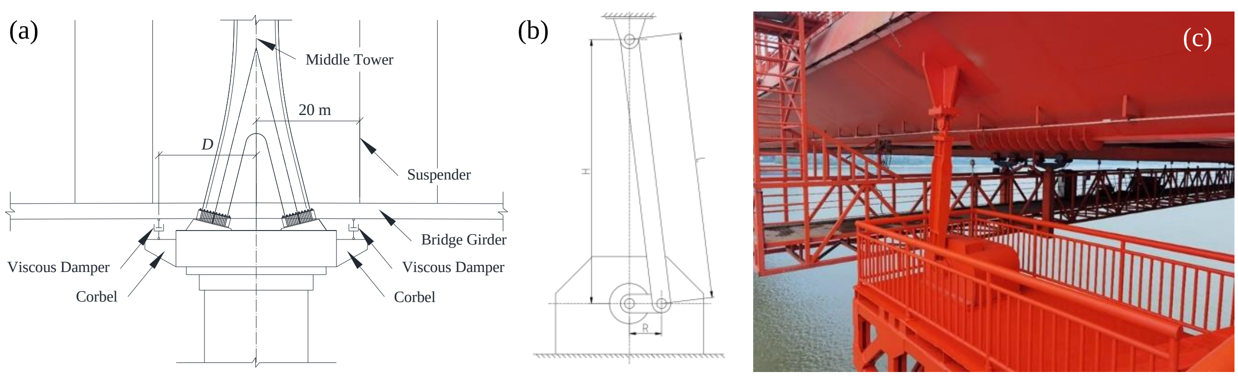

Figure 2. The (a) location (b) schematic and (c) photo of the girder-tower viscous damper

In this project, the damping coefficient of these dampers are optimized according to the optimization algorithm described above, in which the vertical modes 7, 8, and 10-15th that are most likely to suffer from VIV are considered. It took thirteen iterations to reach a relative accuracy of 1%, as shown in Figure 3. Based on the numerical examination, the dampers' designed parameter c was set to 1×10^4 kNs/m.

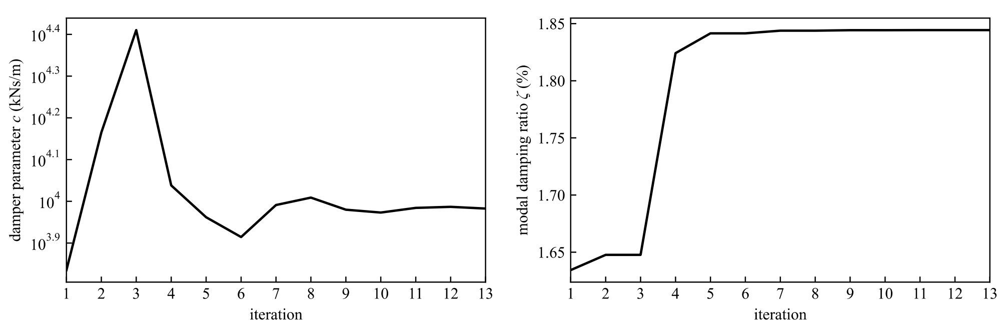

Figure 3. Iteration of the multi-mode optimization

The structural dynamic characteristics were measured under the condition of closed traffic for five nights from July 24 to July 28, 2021. It compared the structural damping ratio under the conditions with or without dampers. To enlarge the response amplitude and improve the measurement accuracy, the continuous jump load was used for excitation. Then the stochastic subspace identification technique was adopted to extract the modal frequencies and the modal damping ratios. The measured damping ratio showed that the installed damper increase the structural damping by three times, and the requirement of the current specification is satisfied. Over 2 years have passed since the dampers were installed, and no VIV has occurred again on the bridge. However, the measured damping ratio was extremely smaller than the numerical results, especially for the high-order modes. It suggests that the local characteristic between dampers and bridge supports plays a significant role in the dampers' performance. A further examination is required for the inconsistency.

5. CONCLUDING REMARK

In the present study, linear viscous dampers are employed to suppress the multi-mode VIV amplitude of long-span bridges. The construction concept and the optimization process were fully addressed. The finding of this paper has been applied to the VIV control of the Yingwuzhou Yangtze River Bridge. The main conclusions are concluded as follows:

(1) Dampers should be placed in a location with large relative modal displacement. Connecting the bridge girder and the bridge tower is a feasible solution. For simply-supported bridges, dampers should be away from the support to ensure the relative modal displacement. The stiffness of the extended corbel is the limitation in choosing the damper location.

(2) Maximizing the minimum modal damping ratio is a reasonable optimization target for multi-mode VIV control. The minimum function is segmented and maintains the unimodal characteristics of the single-mode curve. It is difficult to obtain an analytical solution for the maximum value, but it is easy to obtain a numerical solution by iteration, such as the ternary search algorithm.

(3) The measured damping ratio increased by three times after the dampers were installed. For the mode that occurred VIV, the theoretical VIV amplitude satisfied the requirements of the specification. The measured damping ratio was smaller than that of the numerical result. A further examination will be carried out to evaluate the inconsistency in the future.

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REFERENCES

Chen, Z., 2013. Higher modes' vertical vortex-induced vibrations of suspension bridges-part 2: Aeroelastic model study. 6th European and African Wind Engineering Conference.

Kiefer, J., 1953. Sequential minimax search for a maximum. Proc. Am. Math. Soc. 4, 502–506.

Li, H., Laima, S., Zhang, Q., Li, N., Liu, Z., 2014. Field monitoring and validation of vortex-induced vibrations of a long-span suspension bridge. J. Wind Eng. Ind. Aerodyn. 124, 54–67.

Main, J.A., Krenk, S., 2005. Efficiency and tuning of viscous dampers on discrete systems. J. Sound Vib. 286, 97–122.