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Emergency Measures for Vortex-induced Vibration of Humen Bridge

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ABSTRACT

The sudden vibration of Humen Bridge has aroused widespread concern in society. In order to explore the cause of the vibration and solve the problem, the wind engineering group of Tongji University rushed to the scene. This paper introduces the situation of vortex-induced vibration, and explores the reasons based on on-site testing and investigation. Finally, countermeasures to suppress vortex-induced vibration are given, including temporary control measures and long-term control measures.

1. INTRODUCTION

Humen Bridge is a sea-crossing suspension bridge connecting Nansha District of Guangzhou City and Humen Town of Dongguan City in Guangdong Province, China. It is located above the Pearl River.

On the afternoon of May 5th, Humen Bridge suddenly had a deck vibration, and the vibration continued intermittently for more than 2 hours. The vibration was mainly represented by the vertical vibration of the bridge deck, about 20 times per minute, and the maximal amplitude may be 0.3m; there was no obvious torsional vibration. At that time, the hanger was being replaced on the site of the bridge deck. For construction safety, traffic isolation facilities were set up on both sides of the bridge deck, commonly called water horses. The height was originally known as 1.2 m, but then it was verified to be 0.8 m. The vibration of the bridge deck was initially judged as vortex-induced vibration (VIV), which will not endanger the safety of the suspension bridge structure, but will affect the driving safety.

The VIV of the suspension bridge was judged to be caused by the temporary installation of water horse during the regular maintenance process, which changed the aerodynamic configuration of the closed steel box girder. It was recommended to remove the water horse immediately, strengthen the vibration observation, and pay attention to the safety of the bridge.

After taking measures, the vibration almost stopped. However, on the night of the 5th, new vortex-induced vibration appeared again, but the amplitude was reduced and the frequency was lower.

Based on the actual situation, this paper discusses the causes of VIV and explains the measures used to control vibration in combination with on-site testing and investigation.

2. ON-SITE TESTING AND INVESTIGATION

The structural layout and main girder section of Humen Bridge are shown in Fig.1 and Fig.2.

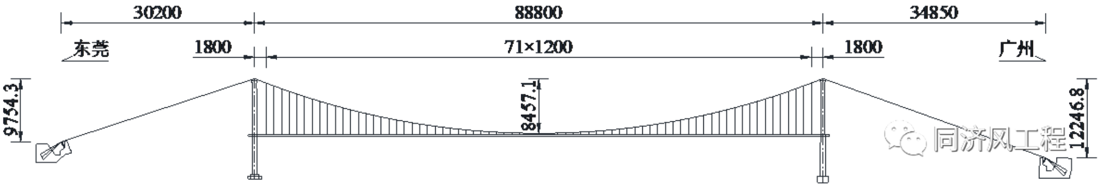


Fig.1 Schematic diagram of structural layout of Humen Bridge (Unit: cm)

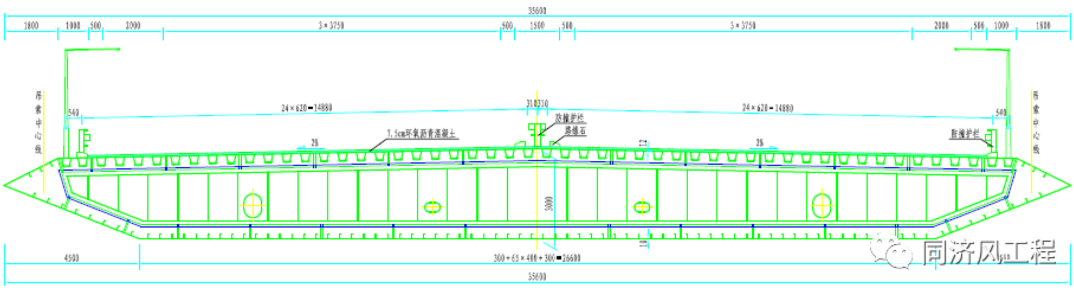


Fig.2 Standard cross-sectional view of stiffening girder of Humen Bridge (Unit: mm)

Video imaging displacement-measured sensor (Fig.3) and portable anemometer were used to observe the displacement response of Humen Bridge and the wind environment of the bridge deck. And the detailed dimensions of the bridge deck, especial railing and the collision wall, were measured on the spot. Meanwhile, the all-weather multi-purpose mobile meteorology monitoring vehicle (mobile laboratory for on-site investigation and testing of wind effects, for short as "wind-chasing vehile") of Tongji University was also used, shown in Fig.4.

Fig.3 Displacement measurement by video imaging technique

Fig.4 Wind-chasing vehicle departed from Shanghai

According to the actual situation, on the afternoon of May 5, the frequency was 0.368 Hz, corresponding to the third-order symmetric vertical bending mode; frequencies of the VIV that occurred later were mainly 0.225 Hz and 0.275 Hz, respectively corresponding to the second-order symmetric vertical bending and second-order antisymmetric vertical bending mode. There was no exact measured value of amplitude on the afternoon of May 5, and the estimated value was 0.31 m (single peak, the same below); the amplitudes of VIV appearing thereafter were 0.145 m and 0.225 m, respectively.

On the spot, the wind speed and structural response of hanging point 9, 14, 18, 25, 30 and 36 along the bridge were detected one by one. The arrangement of observation points is shown in Fig.5. When the wind speed was 8-10 m/s, the incoming wind speed was 90±20 degrees off to the main beam. The maximal unilateral amplitude of VIV was 17.5 cm, and the vibration frequency was 0.23 Hz.

In the early stage of VIV, the arrangement of water horses was the main cause of the vibration. After removal of the water horse, the VIV response was still large. It was judged that the VIV was not completely caused by the water horse, and it was necessary to conduct continue observation of the VIV.

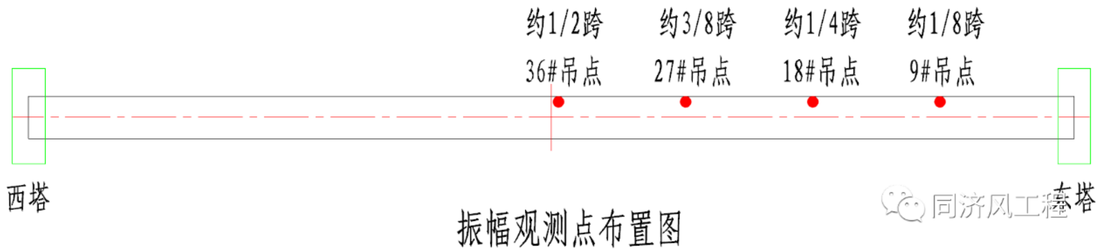


Fig.5 Hangers' number and main amplitude observation points of Humen Bridge

Combining with the on-site investigation, when the water horse was arranged, the vibration frequency at 8-10 m/s wind speed was about 0.368 Hz, while the vibration frequency was 0.225 Hz after the water horse was removed, indicating that the girder's Strouhal number changed significantly before and after the water horse was removed. And that deserved attention.

Besides, two reasonable lidar observation points were selected during the on-site survey, and then Doppler lidar began to monitor the flow around the main girder of the bridge.

3. CAUSES OF VORTEX-INDUCED VIBRATION

According to some facts, the wind speed of 8-10 m/s on the day, the single amplitude of vortex-induced vibration of 19 cm, the vibration frequency of 0.23-0.27 Hz, etc., the cause of VIV was repeatedly discussed, mainly including the friction resistance of the stiffening girder support, the sliding of the main cable saddle, force changing due to the suspension cable replacement and the hinge structure of the hanger anchor with little friction, etc., but they were all ruled out.

Through the CFD calculation which had been preliminarily completed, the influence of the presence or absence of spoilers on the flow pattern of the bridge girder was compared. It was confirmed to be correct that the VIV on the first day was excited by water horse.

After completing the CFD numerical calculation, it was found that the bridge deck and bottom of the girder had a larger vortex. The vortex of the bridge deck had higher frequency and greater energy when there was a water horse, and it can be completely eliminated after installing the spoilers on the top of barriers; the vortex at the bottom of the girder was caused by the outer maintenance rails, and the outer rails needed to be removed to eliminate the vortex. Then the excitation mechanism of two vortex vibrations was clarified.

Furthermore, using lidar to detect that the prototype bridge had regular periodic vortex shedding without additional aerodynamic measures, the root cause of the vortex vibration on the bridge deck was clarified. After the water horse is placed near the railing upstream of the main girder, a regular periodic vortex is generated on the surface of the main girder. The vortex moves downstream along the main girder and decoupled from the Von Karman vortex at the tail of the main girder, forming an air with the same frequency as the bridge structure. The dynamic excitation can qualitatively explain the mechanism and cause of the vortex-induced resonance caused by the water horse. In addition, in the upstream position of the lower surface of the main girder, it is noticed that when the incoming flow passes through the outer maintenance track, it will produce a significant periodic vortex shedding effect, which will also constitute a potential load excitation factor that causes VIV. As shown in Fig.6, when the water horse is removed, the lidar will still observe periodic wake fluctuations downstream of the main girder of the bridge.

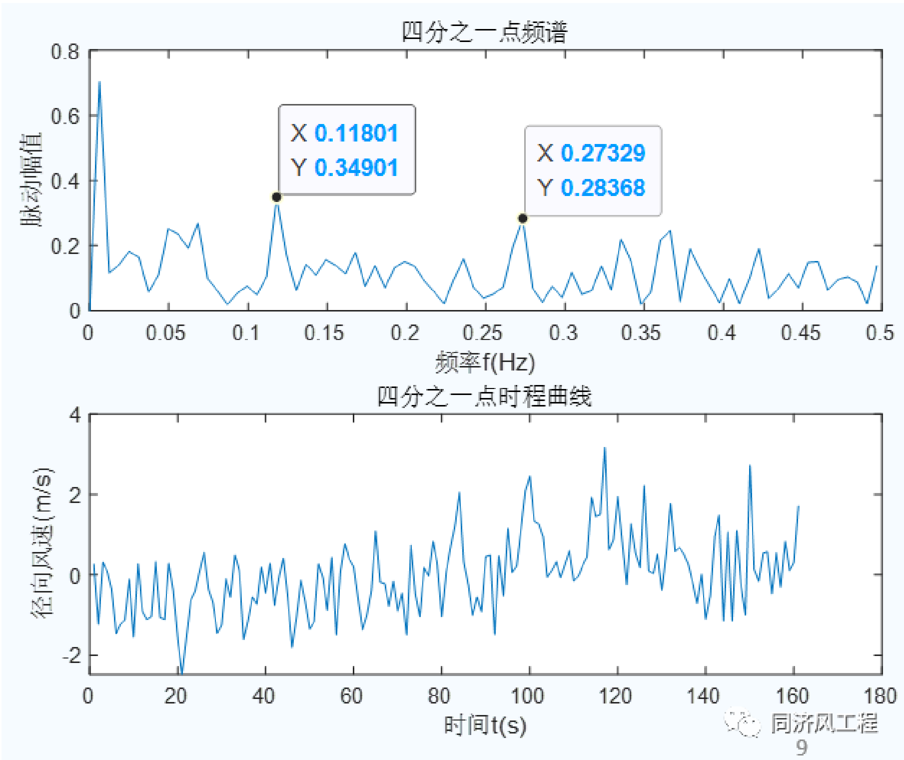


Fig.6 Obvious vortex shedding in the wake flow of the original main girder section of Humen Bridge (after removing the water horse)（8 m/s, 0.23 Hz, 12 cm）

With the help of the lidar, a periodic wake flow pattern was detected downstream of the main girder. Through power spectrum transformation, the main energy components of the wake flow that can be quantified included the resonance frequency (0.273 Hz) of the main girder when the VIV occurred. It was further confirmed that the flow around the main girder included the aerodynamic excitation component that caused the VIV, which was the load excitation source of the main girder for vortex-induced resonance.

At the same time, according to the on-site inspection of relevant units, the measured results of the main vibration mode damping ratio decreased by an average of about 50% compared with the initial construction completion of Humen Bridge.

Therefore, the VIV on the afternoon of May 5 was caused by the water horse, and there was no objection; the VIV that appeared afterwards could now be determined to be due to a decrease in the damping ratio of the structure.

4. TEMPORARY AND LONG-TERM COUNTERMEASURES

The integral box girder cross section itself has a good streamlined aerodynamic shape, but the necessary structures such as railings and maintenance tracks installed at the completion of the bridge stage will weaken its streamlined configuration, causing vortex shedding and large vibrations. Therefore, optimization work for VIV is often carried out on the box girder cross section. Common VIV suppression methods include, but are not limited to, railing and maintenance track adjustment, tuyere optimization, installation of deflectors, diverter plates, spoilers, etc (Zhao et al. 2019;Hu et al. 2019).

It was proposed for the first time to adopt double insurance measures, namely aerodynamic control measures plus damping control measures. Although any of them are sufficient to control VIVs, for safety, it was recommended to use double insurance measures.

It was detected by lidar that the regular periodic vortex can be destroyed when the prototype bridge was equipped with barrier spoilers (Fig.7), and the vortex breaking effect had been initially verified so that it can be used as an effective means to suppress VIVs. And it needs to combine with wind tunnel test to further research its application scope and optimization for structural size involving aerodynamic countermeasures. The wake flow vortex breaking effect is shown in Fig.8.

Fig.7 Experimental installation of spoilers（40 cm long、45 degree inclination; continuous installation within 120 m on the upstream side and 70 m on the downstream side）

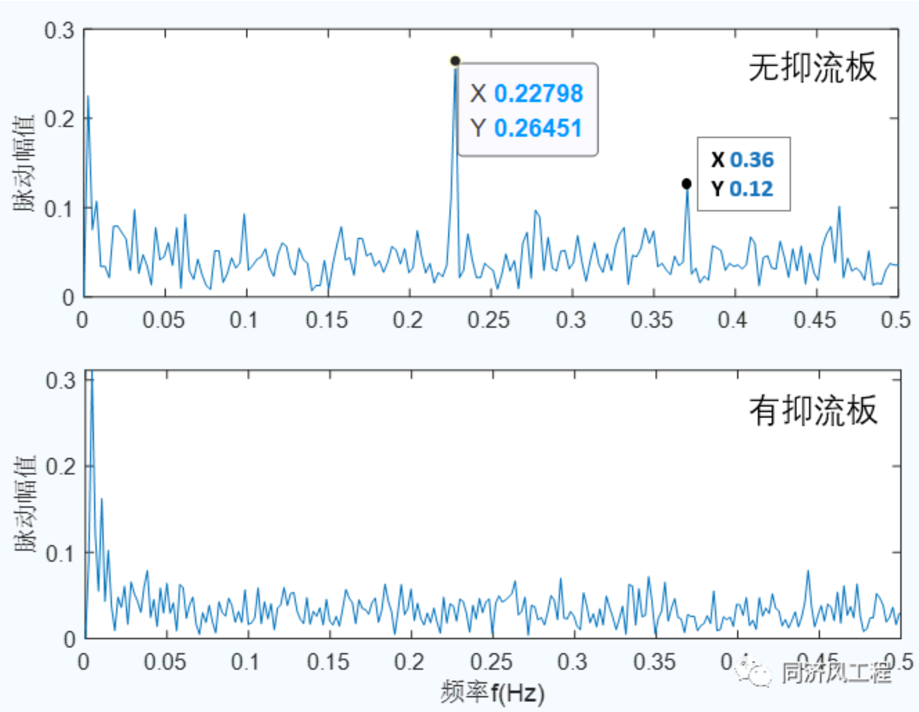
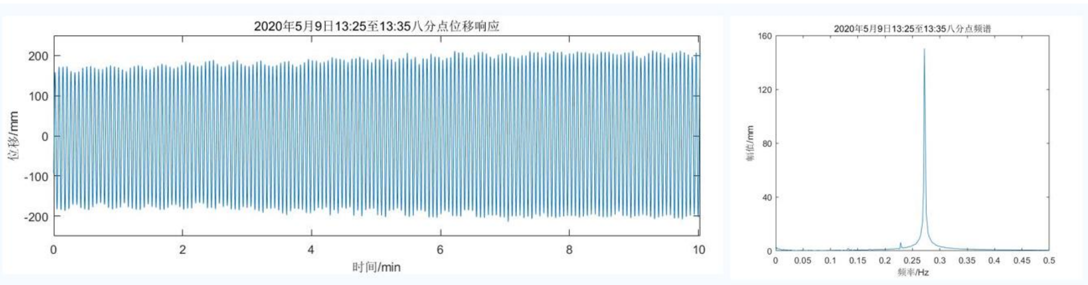
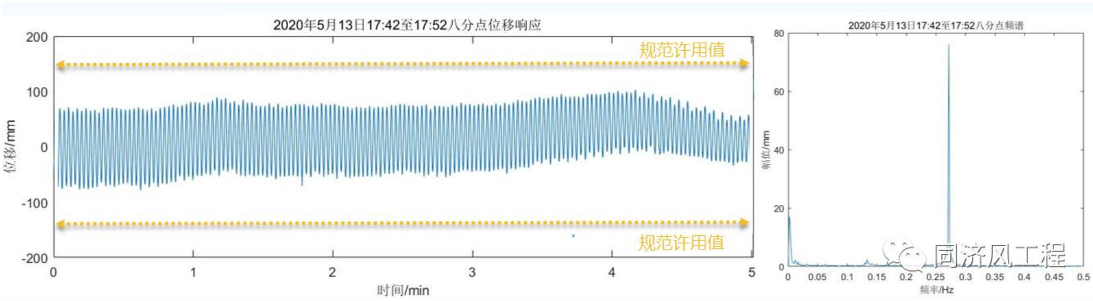


Fig.8 Wake flow vortex breaking effect of spoiler based on comparison of spatial fluctuation velocity spectrum measured by lidar (above without spoilers and below with spoilers)

And VIV response of Humen Bridge before and after installation of spoilers are shown in Fig.9. After applying temporary spoilers, via comparison, it was found that the VIV amplitude under the same vibration mode was reduced by about 50%, and the frequency of VIV also decreased significantly. The value of the vortex amplitude was comparable to the regular driving vibration response of Humen Bridge during normal running stage, indicating that the spoilers had a good mitigation effect, which met requirements of Humen Bridge's safe opening. And it bought valuable transition time for the later application of permanent aerodynamic measures and TMD damper measures.



a) Without spoilers



b) After installation of spoilers
Fig.9 VIV response of Humen Bridge

Meanwhile, it was promised that there was no problem with the implementation of long-term aerodynamic control measures (demolition of the rails), and the rails could be removed one by one from the mid-span to the two sides by using the inner maintenance vehicle track.

Since the decrease in damping ratio also leads to the occurrence of VIV, when controlling the VIV of Humen Bridge, TMD damper (Fig.10) control measure was also proposed. Considering the long design and processing cycle of the TMD damper, it cannot be installed in a short time. Therefore, a method of temporarily setting the water tank in the box girder was proposed alternatively. By introducing the water tank, the equivalent mass could be increased, damping ratio can also be aditional generated by the sloshing of water, forming a temporary additional damping control effect.

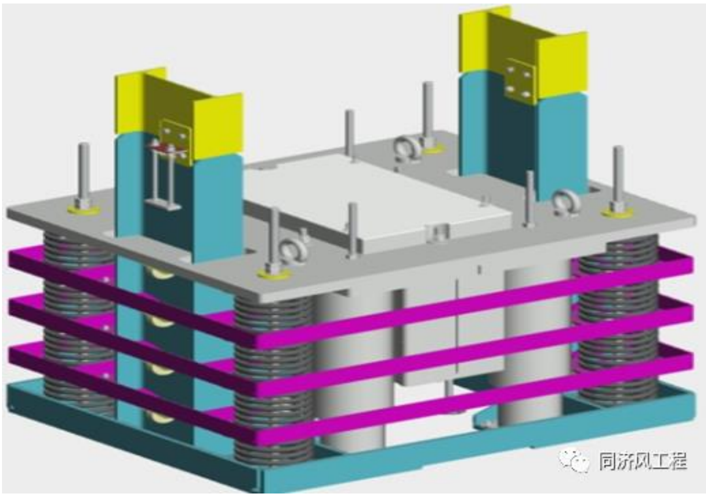


Fig.10 Schematic diagram of TMD damper

To sum up, both aerodynamics control measures and damping control measures are implemented in two phases. For aerodynamics control measures, temporary measures were the installation of spoilers proposed by Tongji University to eliminate vortex on the bridge deck, and long-term measures were the removal of the outer maintenance tracks proposed by Tongji University to eliminate vortices at the bottom of the girder. For, damping control measures, the temporary measure was to adopt the additional water tank scheme recommended by the design institute, that is, the vortex vibration would be controlled by the TLD principle; the long-term permanent measure was the TMD damper proposed by Tongji University.

5. CONCLUSIONS

Combining theoretical analysis, field measurement, numerical calculation and wind tunnel test, the preliminary research conclusions, recommended measures and implementation are as follows:

(1) The vibration phenomenon of the suspension bridge of the Humen Bridge is judged as the wind-induced vibration of the long-span bridge;

(2) According to the wind speed and frequency locking characteristics when wind-induced vibration occurs, it is determined to be VIV, which is mainly manifested as a vertical bending VIV of a single vertical bending vibration mode;

(3) The VIV is mainly related to the wind conditions, structural damping and aerodynamic shape of the bridge. The VIV on the 5th was caused by water horses that were continuously placed on the guardrails on both sides of the bridge deck during the bridge maintenance operation and changed the aerodynamic shape of the bridge;

(4) Long-term, large-amplitude VIV (0.36 Hz) made damping of the suspension bridge structure greatly reduced, causing VIV (0.23 Hz and 0.27 Hz) after the water horse and other temporary facilities were removed;

(5) Two temporary measures are adopted to control VIV, including the aerodynamic control measures of setting spoilers on the top of the railing on both sides of the bridge deck, and damping control measures of the addition of water tanks inside the box beam to improve the quality.

(6) Two long-term measures are adopted to control the vortex vibration and substitute temporary measures, including aerodynamic control measures of removing the outer maintenance rails at the bottom of the box girder (replacement of spoilers) and damping control measures of adding TMD damper(replacement of the water tank).

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