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Damping Estimation of Long-span Bridges to assess the effectiveness of Low Frequency Tuned Mass Dampers to reduce Vortex Shedding Induced Deck Oscillations

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SUMMARY:
After the Humen Bridge in China displayed excessive oscillations in 2019 - 22 years after its completion - vibration tests and a wind study were conducted to identify the cause. With the determination of the natural frequencies and vibration modes it could be concluded that the deck oscillations were due to vortex shedding. Control measures were investigated during wind tunnel studies and it was decided to implement Tuned Mass Dampers to reduce the vortex shedding induced oscillations by increasing the structural damping of the bridge for these modes. The paper herein presented describes the optimization approach which has been undertaken to implement Tuned Mass Dampers in practice, give the very low Eigenfrequencies, the limited space in the bridge deck and the requirement for subsequent installation. Furthermore, results of the monitoring campaign without and with TMDs will presented, which allow wind speed correlations and verified the effects that were investigated during the wind tunnel test. The key parameter to assess the effectiveness of the Tuned Mass Dampers is the structural damping, so a focus of this contribution will be the different methods for in situ damping estimation using the ambient vibration signals. The damping estimation not only allows to monitor the TMD operations but also to assess the dependency of the damping values to the type of excitation respectively the wind speed.
KEYWORDS: Vortex Shedding, Supplementary Damping, Random Decrement Method, Tuned Mass Dampers

1. INTRODUCTION

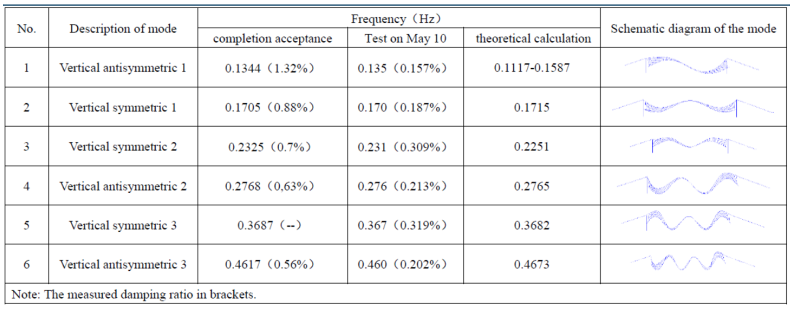
The Humen Bridge in China suffered a sudden vertical vibration of the bridge deck in the afternoon on May 5, 2020. The vibration continued after the bridge deck was closed to traffic, and was calmed down after the removal of temporary water-filled barriers which have been added for the hanger-maintenance construction causing a change of the bridge aerodynamics. However, in the following hours, secondary vertical vibrations were perceivable on the bridge girder. These were determined by field measurement and theoretical analysis as high-order VIVs.

1.1. Introduction of the Bridge

Humen Bridge is a suspension bridge with 888 m main span, crossing the sea gate of the Pearl River in Southern China. The bridge pylons are RC- structures while the deck is a streamlined closed steel box deck (35.6 m wide, 2.99 m high) supported by 72 pair of hangers. After the completion of the bridge in 1997, vibration tests were conducted where the structural damping has been determined and was assessed to be sufficient to avoid excessive deck deflections. However the damping values have significantly dropped during the years, so the low structural damping for the relevant vibration modes has been identified to be cause of the VIV oscillations witnessed in May 2020. During the occurrence of the excessive VIV induced deflections, the wind velocity varied between 4-10 m/s for winds from South to South-East. After the deflections caused a complete closure of the bridge, immediate measures such as water filled barriers - at different locations- to increase the structural damping and spoilers to change the bridge's aerodynamic parameters were implemented but for a permanent solution it was decided to install TMDs.

1.2. Modal Parameters

From initial vibration tests and numerical calculations, the modal parameters have been determined and the theoretical values were confirmed. Table 1.1 summarizes the relevant vibration modes and the corresponding mode shapes.



No.	Description of mode	Frequency（Hz）			Schematic diagram of the mode
		completion acceptance	Test on May 10	theoretical calculation	
1	Vertical antisymmetric 1	0.1344（1.32%）	0.135（0.157%）	0.1117-0.1587	
2	Vertical symmetric 1	0.1705（0.88%）	0.170（0.187%）	0.1715	
3	Vertical symmetric 2	0.2325（0.7%）	0.231（0.309%）	0.2251	
4	Vertical antisymmetric 2	0.2768（0,63%）	0.276（0.213%）	0.2765	
5	Vertical symmetric 3	0.3687（--）	0.367（0.319%）	0.3682	
6	Vertical antisymmetric 3	0.4617（0.56%）	0.460（0.202%）	0.4673	

Note: The measured damping ratio in brackets.

Table 1. Modal Parameters for the relevant modes of the Humen Bridge

During the initial vibration tests, it was also determined that the first four fundamental vibration modes were resonantly excited depending on the occurring wind speed. Figure 1.a shows the magnitude of the deck oscillations and the vibration mode in which they occurred as the function of the wind speed.

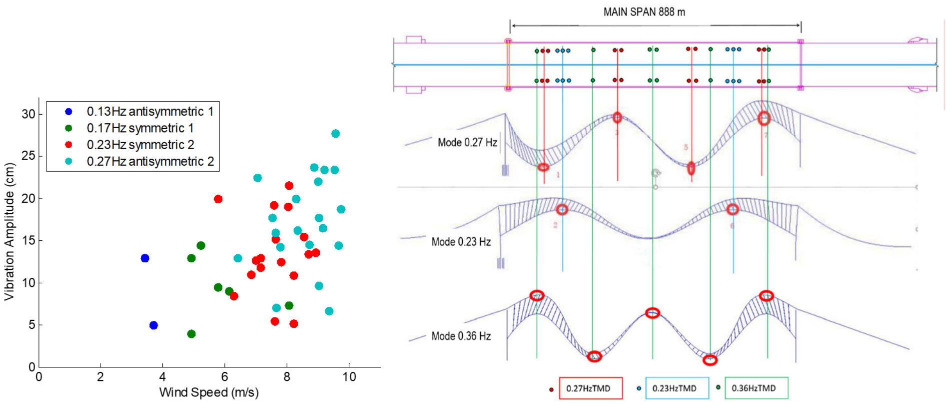


Figure 1. a) Deck Deflections depending on wind speed and vibration mode – b) Applied TMD concept

2. DAMPING CONCEPT

From the initial tests, it became apparent, that the energy introduced at the relevant wind speeds for Mode 1 and 2 was not high enough to cause critical deflections. Although wind speeds higher than 10 m/s did not occur during the initial vibration tests, the probability of higher wind speeds causing a resonant excitation of higher modes with higher resulting deck deflections is very high. So the damping concept also includes the application of TMDs for Mode 4 at 0.36 Hz.

2.1. Optimization TMD parameter

The optimization aspects for every TMD applied to a vibrating structure are to achieve the required reduction with a minimum of additional mass, a maximum of robustness with respect to the relative displacements of the TMD mass. The required reduction, respectively the supplementary damping that is required was determined in wind tunnel tests and by specifying a max. allow deck deflection. To achieve tuning frequencies as it was required for the Humen Bridge, vertically effective, passive TMDs are subjected to high static deflections – 4.7 m for the TMD for Mode 3 (0.23 Hz). Given a height of the bridge deck of less than 3 m, the TMDs had to be optimized with respect to the dynamic relative displacements, while the TMD setup was not to be required specifically robust since natural frequencies were known and the dynamic tests showed that there are no deviations expected with higher traffic or over time.

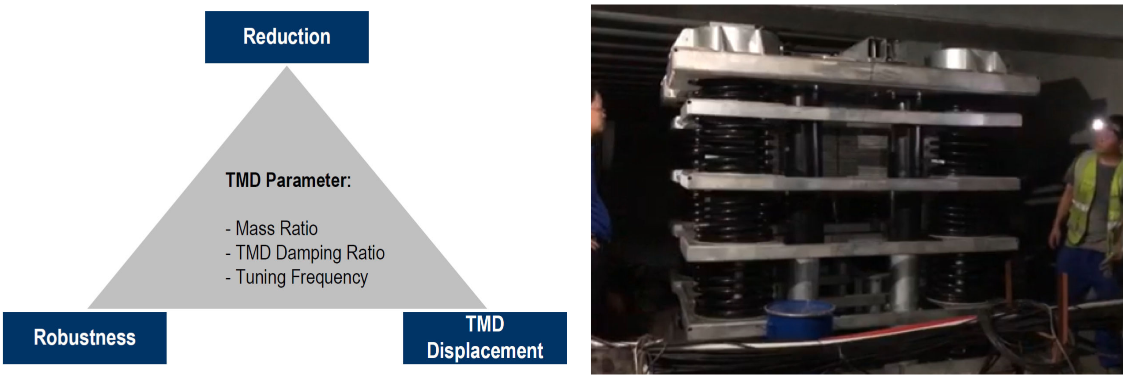


Figure 2. a) Optimization Aspects for the selection of TMD parameters – b) Installed TMD for Mode 3 (0.23 Hz)

2.2. Resulting TMD parameters

Given the above described optimization aspects the following TMD parameters were selected. All TMDs were designed to fit inside the bridge deck to cope with the resulting TMD travel while providing the required reduction effect for the minimum effective TMD mass possible.

Mode	Frequency [Hz]	Modal Mass [t]	TMD Mass [t]	Inherent Damping [%]	theoretical Supplementary Damping [%]	TMD damping Ratio [%]	max. TMD displacement [mm]
3	0.23	8050	60	0.31	2.6	8	160
4	0.27	9880	80	0.21	3.1	8	160
5	0.36	9040	60	0.32	2.6	8	160

Table 2. Optimized TMD parameters

3. MONITORING CAMPAIGN FOR DAMPING ASSESSMENT

To verify the effectiveness of the installed TMDs a long-term monitoring campaign was conducted including different states of the TMD. The TMDs for Mode 4 were installed first and the first campaign started with their installation. After these TMDs proved to be successful, the TMDs for Mode 3 and 5 were installed. During the campaign the accelerations were recorded at multiple locations of the bridge deck to cover all relevant vibration modes (see Figure 3a). Time segments of 20 mins (sampling rate 16 Hz) were stored each data package was processed accordingly.

3.1. Investigated States

During the monitoring campaign the dynamic response of the bridge was determined without TMDs with activated TMDs and again with blocked TMDs. A whole range of wind speeds was covered during the campaign which lasted from July 2021- October 2021.

3.2. Method for Damping Assessment

To determine the structural damping ratio for the relevant modes, the recorded accelerations of the bridge at Pos. 3 were used for an analysis using the Random Decrement Method (RDM). To apply this method the time records were filtered for a band pass of +/- 0.1 Hz for each relevant frequency. The RDM signatures have been determined for different thresholds (40-80% of the max. values) and averaged to establish the resulting damping value. The entire process has been automated for an online damping assessment. The results were determined with 3 different algorithms and proved a good consistency. Figure 3. a) shows the occurring accelerations in October 2020 and the mode in which they have occurred for the investigated states. Figure 3.b shows the determined damping values for the Mode at 0.27 Hz in October 2020.

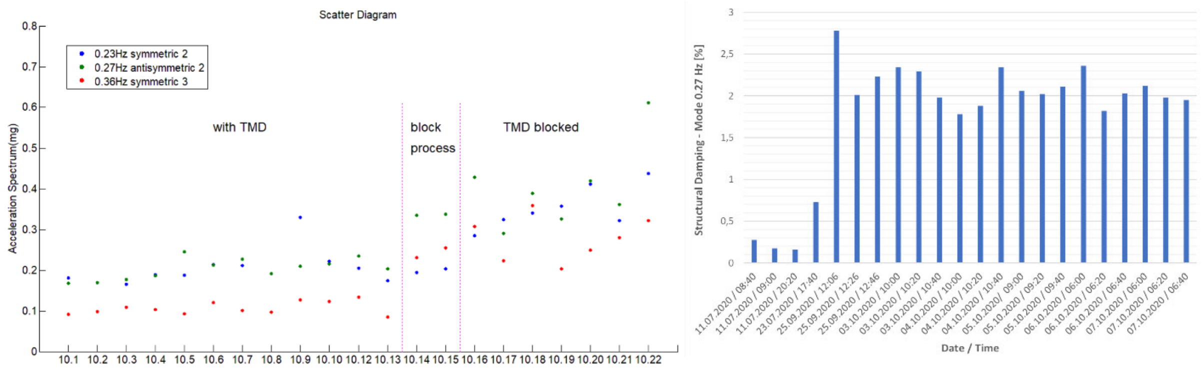


Figure 3. a) Spectral acceleration peaks depending on TMD state – b) Determined Damping Values (RDM)

4. CONCLUSIONS

The installation of in total 40 TMDs to reduce the occurring vortex shedding induced vibrations has been proven to be an effective method for the 2 relevant vibration modes of the Humen Bridge. Despite the challenges of limited installation space and very low tuning frequencies, the Tuned Mass Dampers could be optimized to provide the required supplementary damping (D=0.5%) while TMD mass and relative TMD deflection remain as small as possible. A monitoring campaign from July – October 2021 helped to verify the effectiveness of the devices and to understand the effects of the wind speed on the dynamic response of the bridge.

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