August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Tuned mass dampers for multi-mode vortex-induced vibration control in long-span bridges with dense frequencies

Shengyi Xu [1,2], Genshen Fang [1], Mingjie Zhang [2], Ole Øiseth [2], Yaojun Ge [1]

[1] State Key Lab of Disaster Reduction in Civil Engineering, Tongji University, 200092, Shanghai, China, (xushengyi@tongji.edu.cn, 2222tjfgs@tongji.edu.cn, yaojunge@tongji.edu.cn)
[2] Department of Structural Engineering, Norwegian University of Science and Technology, 7034, Trondheim, Norway, (shengyi.xu@ntnu.no, mingjie.zhang@ntnu.no, ole.oiseth@ntnu.no)

SUMMARY:
This study numerically examined the effect of dense frequencies on the control effectiveness of a tuned mass damper (TMD) for vortex-induced vibration (VIV) of long-span bridges. The force-bridge-dampers system governing equations are derived considering a nonlinear vortex-excited (VEF) force in a polynomial form and simplified through a reduced-order modal expansion of the structural displacement. The study investigates the control effects of TMD for a certain mode VIV while taking into account the influences of other modes with similar frequencies. The results reveal that the TMD effectiveness might be overestimated when placed in the locations with significant modal displacement for other modes with similar frequencies. The study also discusses the number of modes to consider when designing a TMD to control VIV.

Keywords: Multi-mode vortex-induced vibration, long-span bridges, tuned mass damper

1. INTRODUCTION

Vortex-induced vibration (VIV) is a self-excited vibration with finite amplitudes that typically occurs in long-span bridges at low wind speeds. If VIV persists for an extended period and has a relatively large amplitude, it can cause fatigue damage, discomfort to drivers, and even frighten the bridge users. As a result, it is necessary to use countermeasures to mitigate the VIV. Previous studies have described three approaches for suppressing VIV, namely structural, mechanical, and aerodynamic countermeasures (Fujino, 2013). Mechanical countermeasures effectively control VIV regardless of the shape of the bridge girder. The most popular mechanical countermeasure is a tuned mass damper (TMD), which consists of a mass block, a spring and a damping element. The design principles of a TMD attached to a single degree of freedom (DOF) structure under harmonic load have been thoroughly studied (Den Hartog, 1956; Yamaguchi, 1993).
When multiple bridge modes might suffer from VIV, using multiple TMDs with mode-by-mode design is common practice. However, this method ignores the effects of secondary modes. Not considering several modes in the design of TMDs can lead to inaccurate results, especially for long-span bridges with dense frequencies. This study aims to numerically study the influence of various modes on the design of TMDs for VIV control of a long-span bridge considering nonlinear vortex-excitation.

2. GOVERNING EQUATIONS OF FORCE-BRIDGE-DAMPER SYSTEM

Fig. 1 illustrates the layout of the force-bridge-dampers system, with x and y representing the spanwise and vertical coordinates, respectively. Only the vertical vibrations are considered, and we consider the vertex induced aerodynamic loads on the bridge girder. The mass element is attached to the bridge girder via a linear spring element and damping element for each TMD. The displacement of the girder is composed of multiple modes, shown as the red solid line and pink dashed line in the figure.

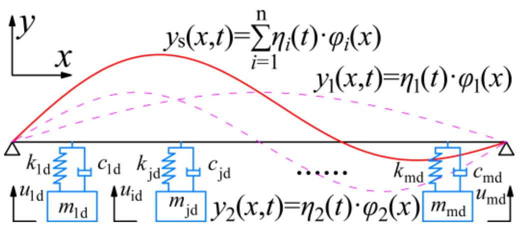


Figure 1. Schematic diagram of the force-bridge-dampers system.

The equation of motion of the force-bridge-dampers system is derived by the virtual work:

$$\int_L \left[m_s(x) \frac{\partial^2 y_s(x,t)}{\partial t^2} + c_s(x) \frac{\partial y_s(x,t)}{\partial t} + EI(x) \frac{\partial^4 y_s(x,t)}{\partial x^4} \right] \cdot \delta y_s(x,t)\, dx + \sum_j \left[F_{jc}(t) + F_{jk}(t) \right] \cdot \delta y_s(x_j,t) = \int_L f_{\text{wind}}(x,t) \cdot \delta y_s(x,t)\, dx \tag{1}$$

$$\left[m_{jd} \ddot{u}_{jd}(t) - F_{jc}(t) - F_{jk}(t) \right] \cdot \delta u_{jd}(x,t) = 0 \tag{2}$$

where $m_s(x)$, $c_s(x)$, and $EI(x)$ represents the distributed mass, distributed damping coefficient, and bending stiffness of the bridge while m_{jd},$F_{jc}(t)$ and $F_{jk}(t)$ are the mass element, damping force and stiffness force of the TMD. The symbol $y_s(x,t)$ represent the displacement of the bridge at the location of x, $\ddot{u}_{jd}(t)$ is the acceleration of TMD, and $\delta y_s(x,t)$ and $\delta u_{jd}(x,t)$ are the virtual displacement of bridge and TMD.

The structural motion can be decomposed into the summation of modal displacements using the superposition principle given by Eq. (3).

$$y_s(x,t) = \sum_n \phi_i(x)\eta_i(t)\, , \delta y_s(x,t) = \sum_n \delta\phi_i(x)\eta_i(t) \tag{3}$$

where $\phi_i(x)$ is the mode shape of the ith mode of the bridge and $\eta_i(t)$ is the modal displacement.

After some processing and organizing, the ordinary differential equations of motion of the force-bridge-dampers system can be obtained as an $n+m$ order matrix form:

$$M \cdot \ddot{\eta} + C \cdot \dot{\eta} + K \cdot \eta = F_{\text{wind}}(\eta, \dot{\eta}), \eta = [\eta_1 \quad \cdots \quad \eta_n \quad u_{1d} \quad \cdots \quad u_{md}]^T \tag{4}$$

where the bridge is assumed to have n modes and be equipped with m TMDs.

The vortex-excited force (VEF) is simulated using the polynomial model. The VEF acting on a specific mode of bridge can be expressed in the modal coordinates using the superposition principle.

$$F_{\text{iwind}} = \rho U^2 D \begin{bmatrix} a_1 \int_0^l \phi_i^2(x)\,dx + a_2 \int_0^l \phi_i^3(x)\,dx \left|\frac{\eta_i}{D}\right| + a_3 \int_0^l \phi_i^4(x)\,dx \left(\frac{\eta_i}{D}\right)^2 \\ +a_4 \int_0^l \phi_i^5(x)\,dx \left|\frac{\eta_i}{D}\right|^3 + a_5 \int_0^l \phi_i^6(x)\,dx \left(\frac{\eta_i}{D}\right)^2 \end{bmatrix} \frac{\dot{\eta}_i}{U} \tag{5}$$

Since VIV typically occurs in a specific mode, it is noted that the VEF is applied to one mode, despite the structure displacement having secondary components from other modes.

3. NUMERICAL RESULTS

A six-span non-navigational continuous bridge of the Shen-Zhong Link is used to demonstrate the impact dense natural frequencies have on the performance of the TMDs. Fig. 2 shows the vibration mode of the bridge. The example considers two vertical bending modes, with dense frequencies of 0.83 Hz and 0.90Hz, respectively. The largest modal displacement of the first mode is almost consistent across all spans, while the modal displacement for the second one is larger in the side spans than in the two middle spans. The performance of one TMD is evaluated, and two possible locations are considered. The two points have identical modal displacements for the first mode. However, the modal displacement of the second mode in location 1 is significantly greater than in location 2. The vortex-induced force is acting on the first mode. The tuned mass damper is also designed to control the first mode and has a mass ratio of 2%. The optimal frequency ratio (0.98) and damping ratio (0.086) of the tuned mass damper are determined based on the theoretical formula for a one-DOF system. The aerodynamic parameters are obtained from wind tunnel test conducted in the TJ-3 boundary layer wind tunnel at Tongji University. The following parameters are adopted: $m_m = 22.2\,\mathrm{kg/s}$, $D_m = 0.667\mathrm{m}$, $f = 5.3\mathrm{Hz}$, $a_1 = 16.6$.

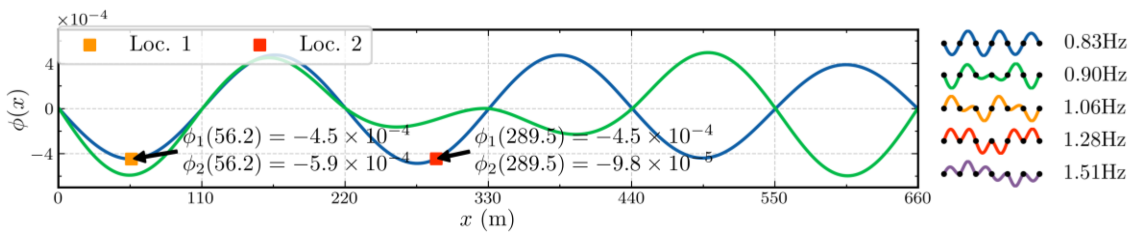
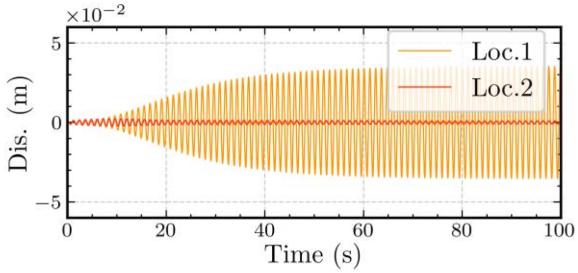


Figure 2. Two different locations of TMDs

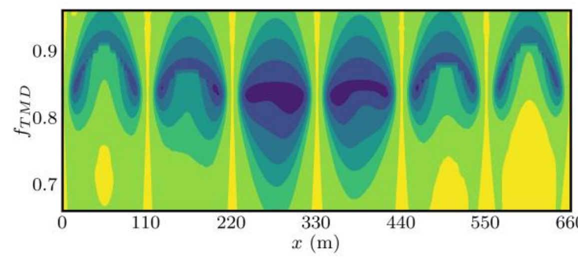
Fig. 3(a) presents the time histories of the point on the girder with the largest displacement after the installation of TMD in two different locations. It illustrates that the presence of mode two significantly impacts the calculated performance of the TMD. When the TMD is placed in location two, where the amplitude of mode two is small, the performance of the TMD is good. The figure also shows that a TMD placed in location one does not perform very well, despite both TMDs being in a point with the same modal displacement of mode one. The outcome at location one differs from the mode-by-mode design result, indicating the need for considering more modes to get a more accurate result, even when only controlling for one mode of vortex-induced vibrations (VIV).

Further analysis of the optimal frequencies of the TMD in various locations on the girder is depicted in Fig. 3(b) and Fig. 3(c). The colour map indicates the maximum displacement after the installation of the TMD. For the middle spans, where mode 2 has small displacements, the optimal frequency is comparable to that in a structure with one DOF. However, in contrast to the results for the middle spans, the optimal frequency of TMD is significantly higher. This is because the amplitude of mode 2 is larger in the side spans. Fig. 3(b) reveals that the performance of the TMD is less robust when it is placed in the side spans and that the optimal location of the TMD may not be in the middle section of the side spans. Fig. 3(c) shows that this effect can be mitigated if the damping ratio of the TMD is increased.

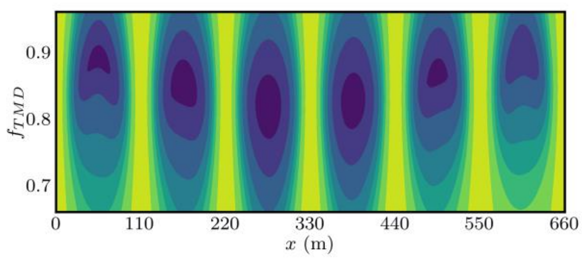
Fig. 3(d) shows a comparison of the maximum displacement of the girder when a various number of modes are considered. If two modes are considered, the calculated control effects are significantly reduced when TMD is installed on the side span. Including a third mode may also decrease the calculated control effects when TMD is placed on the middle spans, although the reduction in performance is less significant than that in the side spans. As the number of modes considered increases beyond 3, the reduction in control effects for TMD installed in any location along the bridge becomes insignificant and results become more accurate. A possible explanation for this might be that the frequencies of higher-order modes are likely too high to have a notable impact on the TMD performance for the lower-order mode. Therefore, even though the VEF only acts on the first mode, it is important to consider at least the first 3 modes with dense frequencies when evaluating the control effects of TMD correctly.



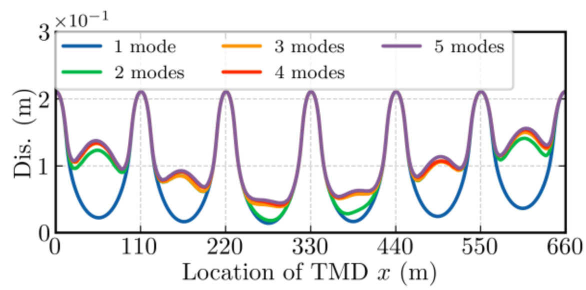
(a) Displacement histories



(b) $\xi_{TMD} = 4.3\%$



(c) $\xi_{TMD} = 14.3\%$



(d) Maximum displacement of the girder

Figure 3. Impact of dense frequencies on control effects of tuned mass damper and optimal parameters

4. CONCLUSIONS

This study examined the impact of dense frequencies on the control effectiveness of TMD with using numerical methods. The results indicated that the effectiveness decreases when located in the locations where there are significant modal displacements for the other modes with similar frequencies. When designing TMD for controlling VIV in a long-span bridge with one mode, more than three modes should be taken into account. Great care should be taken in selecting the number of modes to consider for the bridges with multi-mode VIV vibrations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (52278520, 52108469 and 51978527), the Fundamental Research Funds for the Central Universities (22120220577).

REFERENCES

Fujino, Y. and Siringoringo, D., 2013. Vibration mechanisms and controls of long-span bridges: a review. Structural Engineering International, 23(3), pp.248-268.

Yamaguchi, H. and Harnpornchai, N., 1993. Fundamental characteristics of multiple tuned mass dampers for suppressing harmonically forced oscillations. Earthquake engineering & structural dynamics, 22(1), pp.51-62.

J.P. Den Hartog, 1956, Mechanical Vibrations, 4th ed, McGraw-Hill Book Company, New York, USA.