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Study on the performance of MTMDI in mitigating vortex-induced vibration of parallel bridges

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SUMMARY:
This research presents a multi tuned-mass-damper-inerter (MTMDI) scheme to mitigate the vortex-induced vibration (VIV) responses of parallel bridges. In the scheme, two bridges are linked mutually through two TMDIs. A model of the parallel bridges with the MTMDI under vortex-induced force is constructed, and the model contains two additional cases with TMDIs and tuned-mass-dampers (TMDs) equipped on each bridge separately. VIV responses and parameters are obtained by full-bridge aeroelastic model wind tunnel tests. The performance of the MTMDI scheme with optimal parameters obtained by the multi objective optimization (MOP) method is compared with that of the other two cases. It is demonstrated that the optimal MTMDI scheme is effective in mitigating vertical VIV responses with less requirement on the total mass. The frequency response functions and displacement time histories show that the optimized MTMDI system is more efficient as an attractive alternative to other cases.

Keywords: MTMDI, parallel bridges, VIVs

1. INSTRUCTION

The traditional TMD with greater mass is often used to suppress vibration of buildings and bridges for better control effects. It was observed in previous studies that TMD for VIV mitigation can only be used successfully at large girder heights, since the streamline steel box girder is usually limited in height. In addition, static extension and frequency imbalance of TMD springs pose great challenges in its wide application to bridge structures (Li and Li, 2005).

In recent years, a new control device, TMDI, has been developed (Marian and Giaralis, 2014; Pietrosanti et al., 2017), and it has been widely used in wind resistance of building structures. Zhu et al. (2020) analyzed the application of TMDI to wind resistance analysis of connected buildings, and the results showed that TMDI, compared with TMD, is more effective in suppressing the acceleration response of the two buildings under all wind angles. Since the inertial container in the device can amplify its physical mass, the control effects can be achieved with a less mass. The control device with smaller size and lighter weight not only saves manufacturing costs, but also addresses the limited space for TMDI to be installed in the steel box girder. The characteristics of TMDI feature the device an extensive prospect in vibration control of engineering structures. Xu et al. (2019) applied TMDI to VIV control of bridges, and reasonable TMDI parameters can reduce the vortex-vibration response of the main girder. Hence, TMDI provides another option for VIV control of bridges.

2. ANALYTICAL MODEL

Inerter, as a two-terminal mechanical element, is characterized by the property that the applied force F proportionates to the relative acceleration across its two terminals. Its ideal linear mechanical behavior can thus be expressed as $F = b(\ddot{u}_1 - \ddot{u}_2)$, where $\ddot{u}_1$ and $\ddot{u}_2$ are the acceleration coordinates of the two terminals, and b is the inertance value. Four cases are considered in the present study, as shown in Fig. 1.

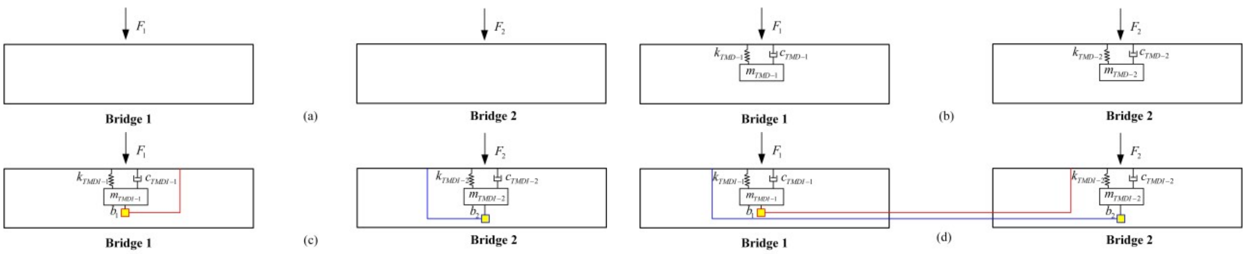

Figure 1. (a) The first case: original structure (b) The second case: two TMDs in each bridge (separately) (c) The third case: two TMDIs in each bridge (separately) (d) The fourth case: two TMDIs linked bridge1 and bridge 2.

If the individual bridge in the parallel bridges system is simplified as a linear SDOF system, then the general equation (Eq. 1) of VIV along y-axis for the parallel bridges with installed TMDIs of the fourth case can be expressed as

$$\begin{bmatrix} M_1 & \mathbf{0} & \mathbf{0} & \alpha_2 \\ \mathbf{0} & M_2 & \alpha_1 & \mathbf{0} \\ \mathbf{0} & \alpha_1^T & M_{\mathrm{TMDI-1}} & 0 \\ \alpha_2^T & \mathbf{0} & 0 & M_{\mathrm{TMDI-2}} \end{bmatrix} \begin{Bmatrix} \ddot{Y}_1(t) \\ \ddot{Y}_2(t) \\ \ddot{Y}_{\mathrm{TMDI-1}}(t) \\ \ddot{Y}_{\mathrm{TMDI-2}}(t) \end{Bmatrix} + \begin{bmatrix} C_1 & \mathbf{0} & \beta_1 & \mathbf{0} \\ \mathbf{0} & C_2 & \mathbf{0} & \beta_2 \\ \beta_1^T & \mathbf{0} & C_{\mathrm{TMDI-1}} & 0 \\ \mathbf{0} & \beta_2^T & 0 & C_{\mathrm{TMDI-2}} \end{bmatrix} \begin{Bmatrix} \dot{Y}_1(t) \\ \dot{Y}_1(t) \\ \dot{Y}_{\mathrm{TMDI-1}}(t) \\ \dot{Y}_{\mathrm{TMDI-2}}(t) \end{Bmatrix} + \begin{bmatrix} K_1 & \mathbf{0} & \gamma_1 & \mathbf{0} \\ \mathbf{0} & K_2 & \mathbf{0} & \gamma_2 \\ \gamma_1^T & \mathbf{0} & K_{\mathrm{TMDI-1}} & 0 \\ \mathbf{0} & \gamma_2^T & 0 & K_{\mathrm{TMDI-2}} \end{bmatrix} \begin{Bmatrix} Y_1(t) \\ Y_1(t) \\ Y_{\mathrm{TMDI-1}}(t) \\ Y_{\mathrm{TMDI-2}}(t) \end{Bmatrix} = \begin{Bmatrix} F_1(t) \\ F_2(t) \\ \mathbf{0} \\ \mathbf{0} \end{Bmatrix} \quad (1)$$

where M, C, K are mass, damping and stiffness matrixes, respectively. $\ddot{Y}, \dot{Y}, Y$ are acceleration, velocity and displacement vectors. α, β, γ are parameters of TMDI. $F_1(t)$ and $F_2(t)$ are the wind force acting on the deck induced by vortex shedding, which can be estimated by the nonlinear semi-empirical model (Simiu and Scanlan, 1986), $F_{1,2} = \rho U^2 D \left[Y_1(K) \left(1 - \varepsilon(K) \frac{y^2}{D^2} \right) \frac{\dot{y}}{U} \right]$, where ρ, U, D are air density, wind velocity and the height of girder, respectively. $Y_1(K)$ and $\varepsilon(K)$ are aerodynamic parameters related to the girder, which are identified by Decay-to-Resonance Method.

3. CASE STUDY

3.1. Wind tunnel tests of parallel bridges

The deck section of a single tower parallel cable-stayed bridge is a bowl-shaped steel box girder. The layout of the deck section is shown in Fig. 2. Configuration of full bridge aeroelastic model test is shown in Fig. 3. The bridge span arrangement is 320 + 320 m.

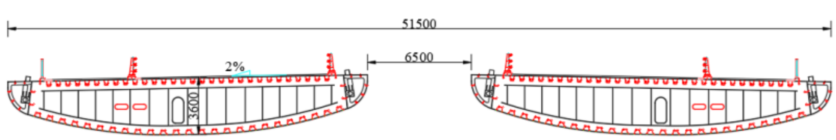

Figure 2. Configuration of parallel girders section (unit: mm).

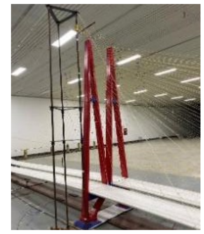

Figure 3. Configuration of full bridge aeroelastic model test: (a) the overall layout (b) detailed layout of the bridge tower and deck.

3.2. Optimized MTMDI parameters

In the fourth case, the eight parameters considered for two TMDIs to investigate the responses reduction are, mass ratio $\mu_{\mathrm{TMDI}-i} = m_{\mathrm{TMDI}-i}/M_i$, inertance ratio $\beta_{\mathrm{TMDI}-i} = b_i/M_i$ (where i =1, 2 represents bridge 1 & 2, b_i is the inertance of TMDI- i and M_i is the total mass of bridge- i), frequency ratio $\upsilon_{\mathrm{TMDI}-i} = \omega_{\mathrm{TMDI}-i}/\omega_i$ (where $\omega_{\mathrm{TMDI}-i}$ and ω_i are natural frequencies of TMDI- i and the VIV frequency of bridge- i) and damping ratio $\zeta_{\mathrm{TMDI}-i} = c_{\mathrm{TMDI}-i}/2\sqrt{(\mu_{\mathrm{TMDI}-i} + \beta_{\mathrm{TMDI}-i})M_i k_{\mathrm{TMDI}-i}}$. The optimization to obtain the above-mentioned parameters was performed for the fourth case. The objective function entails minimization of extreme displacement responses of bridge 1 and bridge 2, subjected to the constraints on $\mu_{\mathrm{TMDI}-i}$, $\upsilon_{\mathrm{TMDI}-i}$, $\beta_{\mathrm{TMDI}-i}$ and $\zeta_{\mathrm{TMDI}-i}$ in the fourth case. The parameters in the wind tunnel tests are converted into those of actual bridge. The equivalent modal mass of the deck per unit length is 15848.6 kg/m. $M_1^s = \bar{m}\int_0^L \varphi_i(x)^2 dx$ is the modal mass for the ith mode with $\bar{m}$ denoting the equivalent mass of the deck per unit length, L is the total length of the bridge 1 and $\varphi_i(x)$ is the modal shape of the deck for the ith mode. The natural frequency of bridge 1 and bridge 2 are 0.4493Hz and 0.4421Hz. In this paper, the responses of the bridge structure are calculated under generalized coordinates, that is, generalized stiffness and generalized damping matrix are used to calculate the responses.

A pareto front obtained from the genetic algorithm (NSGA-II) in terms of the two objectives, i.e., the extreme displacement of bridge 1 and bridge 2, in the fourth case is shown in Fig. 4(a). The point shown inside the circle gives the optimized value of the two objectives. At this point, the response values obtained by the two targets are basically equal and minimum. After the optimal parameters are obtained, the transfer functions for displacement and acceleration responses can be determined as shown in Fig. 4(b) and (c), which help to evaluate the effectiveness of VIV mitigation. It was suggested that the total mass of MTMDI in the fourth case is the least among all the optimal parameters.

3.3. Effectiveness of the MTMDI for VIV mitigation

The displacement in the first case increases with time at the beginning, and its extreme response value remains stable and does not increase when the load continues, showing the amplitude limiting characteristics of VIVs. As for time histories, the displacement response values do not exceed 0.1m. In the second case, the displacement also increases with time at the beginning, but begins to decrease when it increases to less than 0.02m, and continues to remain stable with a certain amplitude in the following time. The displacement values in the third case and fourth case are very similar. Both of them increase continuously at the beginning, and the extreme value is no more than 0.025m. However, after a period of continuous oscillation, the extreme value decreases until the vibration basically comes to an end, achieving the effects of restraining VIVs of bridge 1 as shown in Fig. 5.

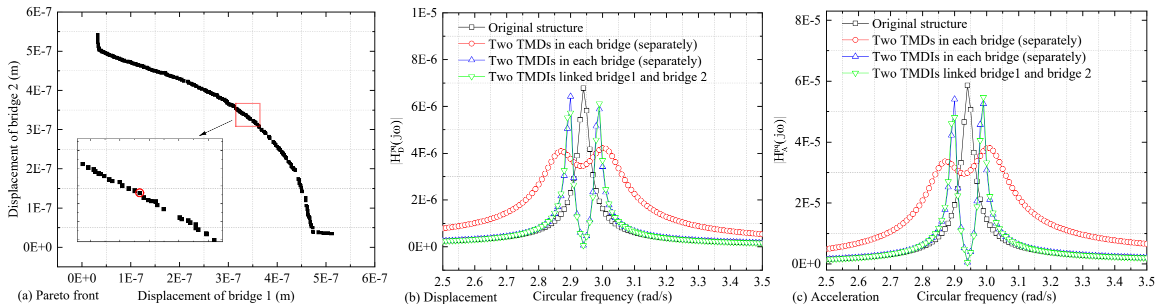

Figure 4. Pareto front corresponding to extreme displacement of the bridge 1 and the bridge 2 (as shown in (a)) and transfer function of the bridge 1 under different cases corresponding: (b) displacement (c) acceleration.

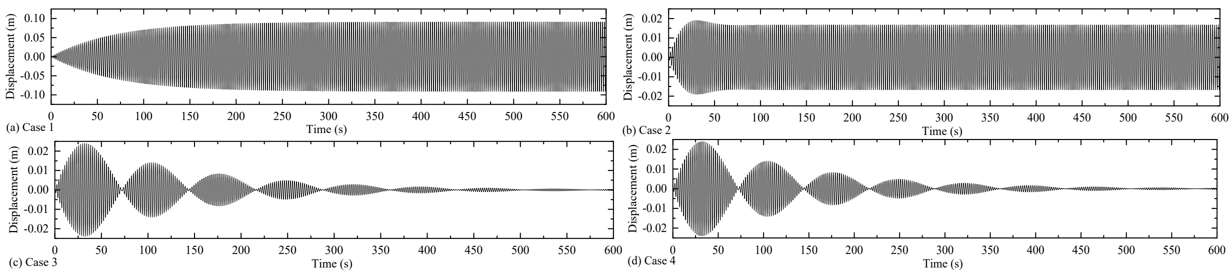

Figure 5. Time histories of displacement corresponding to four cases: (a) case 1 (b) case 2 (c) case 3 and (d) case 4.

4. CONCLUSIONS

According to the frequency response transfer functions of displacement and acceleration, TMDI and TMD systems tune the frequency values of the original structure to two orders of frequency far from the original frequency, and the transfer function values decrease, to some extent. Then, on the grounds of the displacement time histories of the four cases, TMD can only assist to reduce its amplitude to a certain extent, while MTMDI system can effectively suppress VIVs with less requirements on the total mass.

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