Research on Vibration Control of Landscape Tower-TMDI Based on Colliding Bodies Optimization

Liu Yongjie*, Yue Jiahao

School of Civil Engineering and Architecture, Chongqing University of Science and Technology, Chongqing 401331, China

Abstract: Wind load will cause significant vibration of landscape towers, thus bringing strong discomfort to visitors. In order to control structural vibration and reduce this discomfort, in order to study the wind-induced vibration control ability of tuned mass inertial damper (TMDI) on landscape towers, the motion equation of tuned mass damper under wind load is deduced, and the accelerated response spectrum is derived by frequency domain analysis method. The TMDI parameters are optimized by using CBO optimization algorithm to minimize the acceleration of TMDI system of landscape tower, and discussing the ability of TMDI to control wind-induced vibration of structures. The structure is shown as follows: Acceleration response will vary with mass ratio, apparent mass ratio, damping ratio, and frequency ratio. In this paper, dimensionless acceleration is the ratio of acceleration amplitude of the platform equipped with TMDI to that of the platform without TMDI. Within the recommended interval, the control effect of acceleration amplitude is between 16.55% and 26.48%. The acceleration amplitude at the platform still meets the acceleration limit in the specification under the design wind speed, and the vibration reduction of the bent-torsion column - spiral beam landscape tower is realized. The results show that TMDI can effectively control the acceleration response at landscape tower platform.

Keywords: Tuned-mass-damper-inerter; Wind-induced-vibration; Collision Bodies Optimization; Vibration Control Performance; Frequency Domain Analysis Method

DOI: 10.57237/j.cear.2023.02.003

1 Introduction

With the vigorous development of domestic tourism, people have higher and higher requirements for viewing experience. Under this background, many slender and tall sightseeing towers have appeared. Such structures are gentle and have low damping ratio. Therefore, the fatigue damage caused by the continuous and repeated vibration of the structure under the action of breeze and the strength damage caused by the severe vibration of the structure under the action of strong wind will lead to the discomfort of the pedestrian. Both of them need to rely on the damper to control the vibration reduction. Now the development of dampers is moving in the direction of diversification and the damping effect is also greatly improved. In 1911, Frahm proposed a kind of damper called tuned mass damper (TMD) which uses the relation principle of mass and inertia to reduce vibration [1]. The TMD system was initially applied in a super high-rise building in the United States. The application of TMD greatly reduces the wind-

Funding: Open Research Project of University-Enterprise Collaborative Innovation Center of Chongqing University of Science and Technology (Grant No: YKJCX2220622).

*Corresponding author: Liu Yongjie, 3092745427@qq.com

Received: April 28, 2023; Accepted: July 6, 2023; Published Online: July 24, 2023 http://www.cearesearch.org

induced vibration of the structures [2-5], but due to the limitations of quality and space, the actual installation and construction were difficult. In order to reduce the influence of such additional mass on the structure, this paper mainly on the basis of TMD research, by adding flywheel inertiators between the TMD and the main body of the structure to form TMDI, avoid directly increasing the mass of TMD and at the same time, have a better vibration reduction effect. At present, some scholars apply TMDI to research on vibration reduction under stationary white noise excitation or earthquake excitation [6-10]. Under random seismic load, TMDI can play a role of "mass amplification" in the structure, and its vibration reduction effect exceeds that of TMD [11]. By coupling a "habitual container b", or TMDI, to the regular mode TMD, the principle is shown in Figure 1.

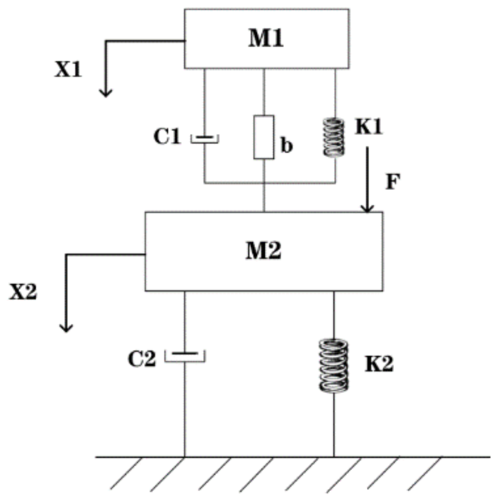


Figure 1 Schematic diagram of TMDI principle

De Domenico [8] enhanced the seismic effect of the infrastructure by utilizing the characteristics of TMDI, Giaralis [12] studied the effect of TMDI on wind-induced vibration of high-rise structures by numerical simulation. Lee [13] studied the control effect of inertia device on TMDI on wind induced vibration of flexible structures. These studies show that TMDI has a good damping effect on wind-induced vibration of structures, but the research difficulty lies in the strong dependence of TMDI on frequency ratio and damping ratio. Therefore, an important part of TMDI optimization design problem is the selection of optimization method, which usually requires an optimization process to obtain the optimal TMDI parameters of control objectives. In addition to the usual mathematical methods, with the rapid growth of computer computing power, meta-heuristic algorithm emerged. Hartog [14] first proposed the fixed-point theory, according to the main structure frequency response function, the analytical solution of the optimal parameters of the damper under harmonic excitation is obtained by Vieta theorem. Although the fixed-point optimization method can find the optimal solution in the local scope, its computational cost is very expensive. In addition, with the increase of structural complexity, the calculation of fixed point theory becomes more difficult. Compared with other heuristic algorithms, collision optimization algorithm can optimize the solution with fewer iterations, faster convergence and more stable results. Therefore, the CBO method is more superior in optimizing the parameters of tuned mass damped inertial damper.

In order to solve the sensitivity of TMDI to damping ratio and frequency ratio, the TMDI control performance under random wind load was analyzed in this paper, and by using the method of frequency domain analysis, we can derive the mathematical expression of acceleration spectrum. According to the obtained formula, the optimal design parameters of CBO were determined, and then TMDI control performance under different mass ratio and apparent mass ratio was compared. The research results show that TMDI can greatly control the acceleration response of landscape tower platform and greatly reduce the discomfort caused by vibration.

2 Project Overview

This paper takes a curved and twisted pillar-spiral beam landscape tower in a western city of China as the research background. The curved and twisted pillar-spiral beam landscape tower has important significance to show the image of the city. The tower is divided into tower body and streamer.

3 Governing Equation of Combination of Landscape Tower and TMDI System

The acceleration at the upper platform of the landscape tower with twisted column and spiral beam is relatively large, resulting in poor pedestrian comfort. Therefore, TMDI is selected to be installed at the upper platform of the landscape tower, as shown in Figure 2.

The motion equation of TMDI in Figure 2 is:

$$M_1^*\ddot{X}_1 + C_1^*\left(\dot{X}_1 - \dot{X}_2\right) + K_1^*\left(X_1 - X_2\right) = 0 \quad (1)$$

Where, M_1^* is the generalized mass of TMDI, C_1^* is the generalized stiffness of TMDI, K_1^* is the generalized stiffness of TMDI, X_1 is the displacement of TMDI with respect to the main structure, and $\boldsymbol{X}_2$ is the displacement of the main structure with respect to the ground. The subscripts of the above formulas represent the main structure.

The motion equation of the main structure in Figure 2 is:

$$\mathbf{M}_2\ddot{\mathbf{X}}_2 + \mathbf{C}_2\dot{\mathbf{X}}_2 + \mathbf{K}_2\mathbf{X}_2 = \mathbf{F} + \mathbf{F}_{Ti} \quad (2)$$

Where, M_2 is the mass matrix of the main structure; C_2 is the damping matrix of the main structure; K_2 is the stiffness matrix of the main structure; F the wind load of the main structure; Let X_3=X_1-X_2, X_3 is the displacement of TMDI with respect to the main structure.

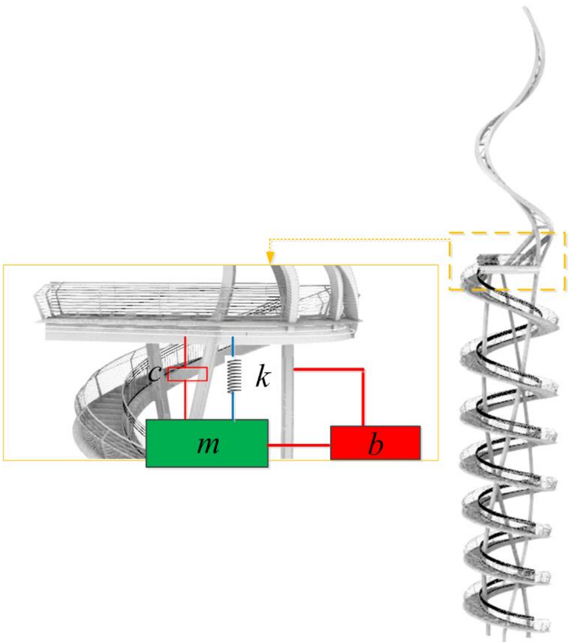


Figure 2 Schematic diagram of TMDI placement position

Equation (1) and (2) are obtained by mode decomposition method:

$$\begin{aligned}&\ddot{q}_2 + 2w_2\zeta_2\dot{q}_2 + w_2^2q_2 = \\ &F_2^*/M_2^* + \mu\phi_2(z)\left(2w_1\zeta_1\dot{X}_3 + w_1^2\ddot{X}_3\right)\end{aligned} \quad (3)$$

$$\phi_2(z)\ddot{q}_2 + \ddot{X}_1 + 2w_1\zeta_1\dot{X}_3 + w_1^2X_3 = 0 \quad (4)$$

In the formula, q_2 is the generalized modal coordinate of the structure, w_1 is the frequency of TMDI, w_2 is the circular frequency of undamped vibration of the structure, ζ_1 is the damping ratio of TMDI, ζ_2 is the damping ratio of the structure, M_{ca} is the mass of the platform, μ is defined as the mass ratio of TMDI and the main structure, = M_1/M_2.

The variance of the downwind displacement resonance component of the main structure is:

$$\sigma_{u2,r} = \phi_2(z)\frac{1}{M_2^*}\left\{\begin{matrix}\int_0^H\int_0^H\phi_2(z_a)\phi_2(z_b)\sigma_{f'}(z_a)\sigma_{f'}(z_b)\\ coh(z_a,z_b)dz_adz_b\int_0^\infty\left|H_{2l}(n)\right|^2dnS_f(n_t)\end{matrix}\right\}^{\frac{1}{2}} \quad (5)$$

Acceleration amplitude is expressed as:

$$\ddot{X} = gw^2\sigma_{u2,r} \quad (6)$$

Where: g is the peak factor.

4 Solution Method Based on Collider Optimization Algorithm

In the ideal state, collisions between objects are momentum conserved, that is, the total momentum of the objects before and after the collision is the same.

The formula is expressed as follows:

$$m_1v_1 + m_2v_2 = m_1v_1' + m_2v_2' \quad (7)$$

$$\frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 = \frac{1}{2}m_1v'^2 + \frac{1}{2}m_2v_2'^2 + Q \quad (8)$$

Where, v_1, v_2 are the initial velocities of the two objects before collision, v_1' and v_2' are the final velocities of the two objects after collision, and Q is the kinetic energy loss caused by collision. The velocity after collision can be obtained by combining formula (7) and (8):

$$v_1' = \frac{(m_1 - \varepsilon m_2)v_1 + (m_2 - \varepsilon m_2)v_2}{m_1 + m_2} \quad (9)$$

$$v_2' = \frac{(m_2 - \varepsilon m_1)v_2 + (m_1 + \varepsilon m_1)v_1}{m_1 + m_2} \quad (10)$$

$$\varepsilon = \left|\frac{v_2' - v_1'}{v_2 - v_1}\right| = \frac{v'}{v} \quad (11)$$

In the formula, ε is the recovery coefficient, defined as the ratio of relative separation speed to relative approach speed, to ensure that a stable balance between global and local search can be maintained throughout the optimization process.

Under the pre-set boundary conditions, the position of the collision body is generated randomly, as shown in the following formula [15]:

$$x_i = x_{min} + rand(x_{m\, x_i = x_{min} + rand(x_{max} - x_{min}), i=1,\dots,n\, x} - x_{min}) \quad i = 1,\dots,n \tag{12}$$

Where, x_i is the position of the ith collider after initialization, and x_{min} is the maximum and minimum values of the parameters to be optimized respectively. rand() is a random number between [0,1].

For colliders, the objective function is calculated, as shown in Equation (13).

$$obj_i = z(x_i), i = 1,\dots,n \tag{13}$$

Where, obj_i is the target function. The mass of the collider is inversely proportional to its fitness value.

According to the fitness function value from small to large, the population relationship is divided into static group and collision group. The initial velocity of the moving group before collision is the difference of the relative position of the collider.

$$\begin{cases} Stationary\ group: & v_i = 0, i = 1,2,\dots,\frac{n}{2} \\ Moving\ group: & v_i = x_i - x_{i-n/2}, i = \frac{n}{2}+1,\dots,n \end{cases} \tag{14}$$

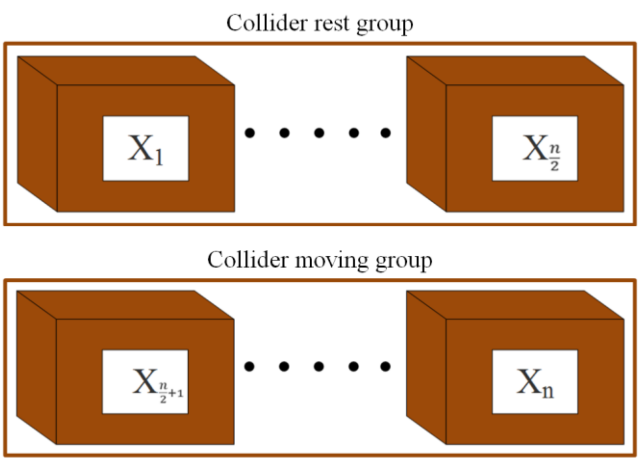


Figure 3 Grouping diagram of colliders

When the collider in the second part collides with the collider in the first part, the velocity of the rest group and the moving group is created, which is used to describe the state after the collision, as shown in Figure 4.

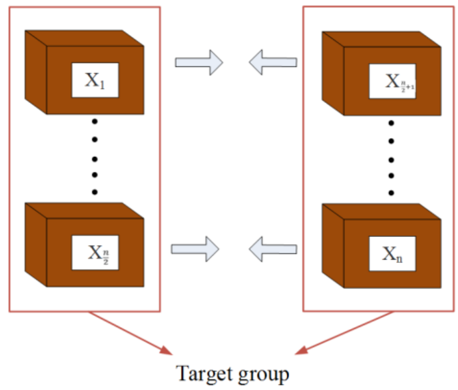


Figure 4 Collision object group

The post-collision velocity is used to calculate the new position of the collider, as follows:

$$\begin{cases} Stationary\ group: & x_i^{new} = x_i + rand \circ v_i', i = 1,\dots,\frac{n}{2} \\ Moving\ group: & x_i^{new} = x_{i-n/2} + rand \circ v_i', i = \frac{n}{2}+1,\dots,n \end{cases} \tag{15}$$

Where, x_i^{new}, x_i and v_i' are respectively the position after update, the position before update and the velocity after collision. *rand*() is the random number between [-1, 1]. The flowchart of CBO algorithm is shown in Figure 5.

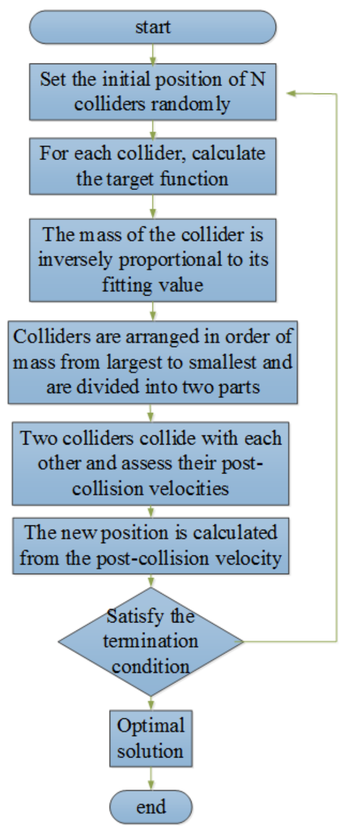


Figure 5 CBO calculation flow chart

The objective function of this paper is the maximum amplitude of the acceleration response ($\ddot{X}$). It can be seen from Equation (6) that both damping ratio and frequency ratio of TMDI affect the amplitude response of acceleration. Therefore, the acceleration amplitude response can be controlled effectively by selecting reasonable optimization parameters. In this study, the optimization process took 20 colliders, 20 steps, and 10 runs. Finally, we take the average of the optimization results of these 10 runs. In the MATLAB vector representation, the range of values for the preselected values is as follows:

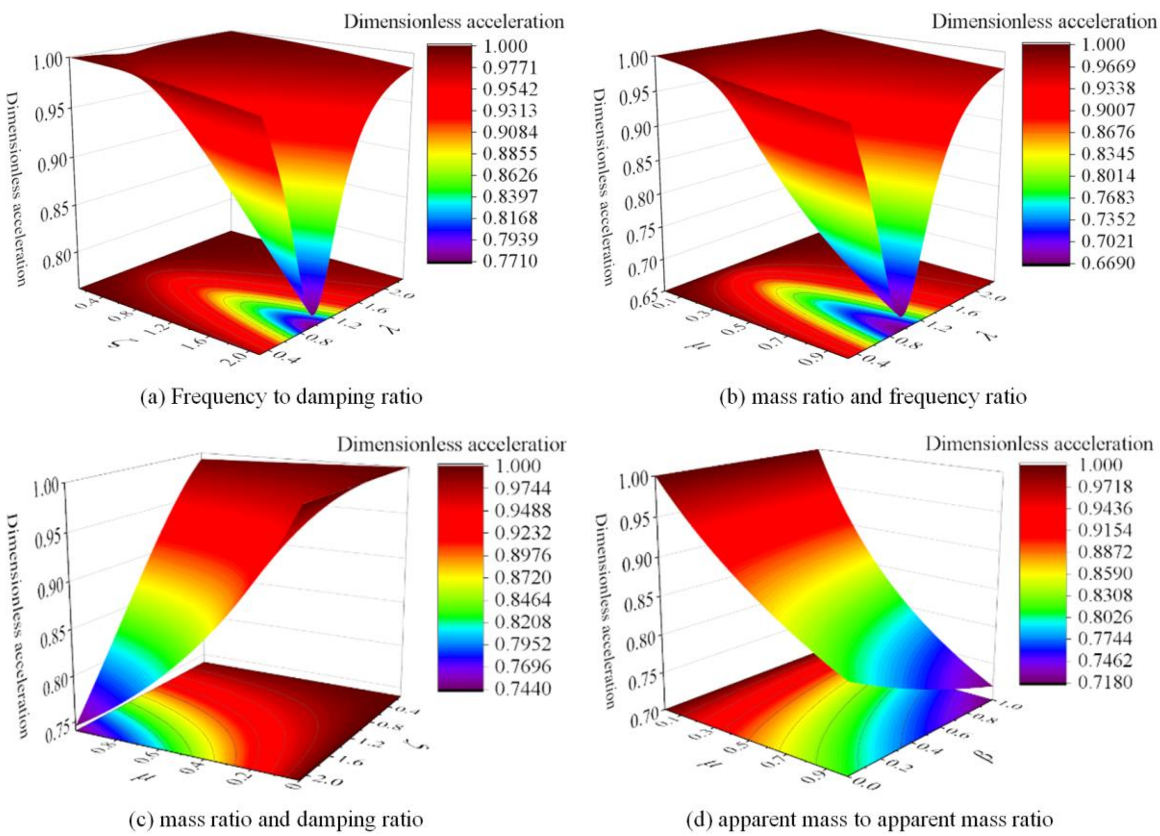
$$\mu=[0:0.01:1],\quad \beta=[0:0.01:1] \tag{16}$$

At this stage, we will take the acceleration response as the objective function and the frequency and damping ratio as the design variables. In the MATLAB vector representation, the range of tuning values is shown as follows:

$$\lambda=[0.1:0.02:2.1],\quad \zeta=[0.1:0.02:2.1] \tag{17}$$

5 Effectiveness Analysis of TMDI

The purpose of this study is to investigate the effectiveness of the ungrounded supporting mass damper (TMDI) on acceleration response control effect at curved torsional column and spiral beam landscape tower platform. By changing the mass ratio μ, apparent mass ratio β, frequency ratio λ and damping ratio ζ, the influence of each parameter on the maximum displacement response of bent-spiral beam landscape tower structure can be studied. In the figure, dimensionless acceleration is the ratio of acceleration amplitude of the platform equipped with TMDI to that of the platform without TMDI. The acceleration contour plot shows obvious color changes from the lower left corner to the lower right corner, indicating that the acceleration response changes with the change of various parameters.



(a) Frequency to damping ratio

(b) mass ratio and frequency ratio

(c) mass ratio and damping ratio

(d) apparent mass to apparent mass ratio

Figure 6 Influence of each parameter on acceleration response

By comparing Figure 6(a) and (b), it can be found that the frequency ratio has an obvious influence on the amplitude of acceleration response. When the frequency ratio λ is 1, TMDI and the frequency of the landscape tower produce resonance phenomenon, and the frequency ratio λ has the maximum influence on the control of the amplitude of acceleration response. In the simulation condition of mass ratio μm and damping ratio ζ when frequency ratio λ is 1, the maximum control effect of acceleration response amplitude is between 22.9% and 33.1%, which makes the acceleration amplitude of the platform equipped with TMDI drop from 0.205m/s^2 without TMDI to below 0.158m/s^2.

By comparing Figure 6(c) and (d), it can be seen that the control effect of acceleration response amplitude at the platform increases with the increase of mass ratio μ, apparent mass ratio β and damping ratio ζ. When the apparent mass β is 0, TMDI is equivalent to TMD. As the increase of the apparent mass ratio β reduces the amplitude of acceleration response, it is also verified from the side that TMDI is better than TMD in terms of vibration reduction effect. Secondly, it can be seen that apparent mass ratio β and mass ratio μ have better control effect on the amplitude of acceleration response than mass ratio μand damping ratio ζ respectively.

From figure 6 (a), (c) of the contour can be given apparent quality ration β, including quality ratio μ, frequency ratio λ and the damping ratio ζ recommended interval [0.2,0.4], respectively [0.3,0.6], [1.8,2.1], [0.8,1.2], the recommended range, The acceleration amplitude control effect is between 16.55% and 26.48%, which makes the acceleration amplitude of the platform equipped with TMDI drop from 0.205m/s^2 without TMDI to below 0.171m/s^2, realizing the vibration reduction of the landscape tower with twisted column and spiral beam.

6 Conclusion

In this paper, the motion equation of landscape tower-TMDI under random wind load is established, the acceleration response of landscape tower acting on TMDI is analyzed based on frequency domain analysis method, and the response of spiral beam landscape tower-TMDI structure is optimized based on collider-based algorithm. The main conclusions are summarized as follows:

(1) Through reasonable assumptions, the structure of landscape tower-TMDI system is simplified, and the acceleration amplitude formula at landscape tower-TMDI platform under the action of high wind speed under the design wind speed is derived. The results show that the control effect of random wind load is mainly affected by λ, ζ for the structure dominated by the basic modes. In order to provide sufficient vibration damping, a non-grounded connection is adopted, and the two ends produce opposite acceleration, so as to reduce the vibration.

(2) The parameters of TMDI are optimized by CBO optimization algorithm. The results show that when the frequency ratio λ is below 0.6 or above 1.4, the control degree of other parameters on the amplitude of acceleration response is less than 10% at most. Compared with the acceleration response at the uncontrolled landscape tower platform, the frequency ratio λ is [0.8,1.2], the damping ratio ζ is [1.8,2.1], the mass ratio μ [0.3,0.6], and the apparent mass ratio β is [0.2,0.4]. The acceleration amplitude control effect is between 16.55% and 26.48%, and the acceleration amplitude at the upper platform of the bent-torsion column and spiral beam landscape tower is reduced from the original 0.205m/s^2 to less than 0.171m/s^2.

References

[1] Frahm H. Device for damping vibrations of bodies: U.S. Patent 989,958 [P]. 1911-4-18.

[2] Laura P A A. Discussion: Performance of Multiple Mass Dampers under Random Loading [J]. Journal of Structural Engineering, 1996, 122 (8): 981-982.

[3] Lin J L, Tsai K C, Yu Y J. Bi-directional coupled tuned mass dampers for the seismic response control of two-way asymmetric-plan buildings [J]. Earthquake Engineering & Structural Dynamics, 2011, 40 (6): 675-690.

[4] Huang M, Huang M. Integrated Structural Optimization and Vibration Control for Improving Dynamic Performance of Tall Buildings [J]. High-Rise Buildings under Multi-Hazard Environment: Assessment and Design for Optimal Performance, 2017: 133-156.

[5] Patil V B, Jangid R S. Optimum multiple tuned mass dampers for the wind excited benchmark building [J]. Journal of Civil Engineering and Management, 2011, 17 (4): 540-557.

[6] Zhao S, Yan Z, Savory E. Design wind loads for transmission towers with cantilever cross-arms based on the inertial load method [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2020, 205: 104286.

[7] Taflanidis A A, Giaralis A, Patsialis D. Multi-objective optimal design of inerter-based vibration absorbers for earthquake protection of multi-storey building structures [J]. Journal of the Franklin Institute, 2019, 356 (14): 7754-7784.

[8] De Domenico D, Ricciardi G. Optimal design and seismic performance of tuned mass damper inerter (TMDI) for structures with nonlinear base isolation systems [J]. Earthquake engineering & structural dynamics, 2018, 47 (12): 2539-2560.

[9] De Domenico D, Ricciardi G. An enhanced base isolation system equipped with optimal tuned mass damper inerter (TMDI) [J]. Earthquake engineering & structural dynamics, 2018, 47 (5): 1169-1192.

[10] Giaralis A, Taflanidis A A. Optimal tuned mass-damper-inerter (TMDI) design for seismically excited MDOF structures with model uncertainties based on reliability criteria [J]. Structural Control and Health Monitoring, 2018, 25 (2): e2082.

[11] Ruiz R, Taflanidis A A, Giaralis A, et al. Risk-informed optimization of the tuned mass-damper-inerter (TMDI) for the seismic protection of multi-storey building structures [J]. Engineering Structures, 2018, 177: 836-850.

[12] Giaralis A, Petrini F. Wind-induced vibration mitigation in tall buildings using the tuned mass-damper-inerter [J]. Journal of Structural Engineering, 2017, 143 (9): 04017127.

[13] Lee L, Allen D. Vibration frequency and lock-in bandwidth of tensioned, flexible cylinders experiencing vortex shedding [J]. Journal of Fluids and structures, 2010, 26 (4): 602-610.

[14] Den Hartog J P. Mechanical vibrations [M]. Courier Corporation, 1985.

[15] Liu X P, Li S Y, Wu C Y, Zhong Y L, Bian Y F. Research on Vibration Control of Power Transmission Lines-TMDI Based on Colliding Bodies Optimization. Buildings. 2022, 12 (12): 2200.