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Torsional Vibration Control of High-rise Building with Large Local Space by Using Tuned Mass Damper

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Abstract. According to the shake table test results of a high-rising building with large local space, the dynamic characteristics of such structure are complex and the torsional mode becomes the first mode, while the torsional responses under earthquake excitation, especially of the floor just above the large local space, are very remarkable. Special measures are required for such structural system for maintaining its seismic safety. In this research, the bidirectional Tuned Mass Damper (TMD) is employed for reducing the torsional vibration of the high-rising building with large local space. The optimization of the TMD parameters, such as natural frequency, damping ratios and mass ratio, is performed. The time history analysis results indicate that the proposed bidirectional TMD is very effective in torsional vibration control.

Introduction

For some high-rising buildings, large local space is very useful for the special function needs, such as the function of a conference hall and hotel lobby. The high-rising structures with large local space obviously belong to complex irregular structural system which may suffer serious damages induced by the torsional vibration under earthquake condition. A shake table test on such structural system has been performed by Zhao et al. [1] that indicate the dynamic characteristics are complex and the torsional mode has become the first mode of the structure. The torsional responses under earthquake excitation, especially of the floor just above the large local space and the structural members nearby, are quite remarkable and special measures are required for such structural system for maintaining its seismic safety.

During the past 30 years, several innovative passive and active control devices have been developed and constructed for reducing vibrations in structures caused by wind loads and earthquakes [2, 3]. Tuned Mass Damper (TMD) is an example of such devices, and their design has been a subject of much interest to researchers all over the world, with a wealth of theoretical and experimental work in the literature [4]. A simple unidirectional TMD consists of a single mass m, connected to the structure by a viscous dashpot c and a linear spring k. The mass is constrained to move in one direction alone, and is usually most effective when the response of the structure is predominantly in the direction in which the damper can move. However, if the structural response is such that there is a very small component of its motion along the path of the damper, or a quite large component perpendicular to the path of the damper, or the structure is suffered large torsional responses, then the unidirectional TMD may not be very effective. For reducing the seismic responses of the complex building structures, such as the high-rising building structure with large local space, a bidirectional TMD system may be applied.

In this paper, the seismic behavior and the torsional responses of a complex high-rising building with large local space are studied. A simple multi-floor building model is established and the bidirectional TMD system is employed to reduce the torsional responses of the structure under seismic condition. The numerical results indicate that the well-designed bidirectional TMD system is effective in reducing the torsional responses of the whole structure as well as the top of the large local space.

Mechanical Model of the Building

A sample multi-floor model of a building is considered in this research. The mass of the structure is concentrated at the floors, which are linked by massless springs to represent horizontal and rotation stiffness of the walls and columns. Each floor has a mass center and a stiffness center, and the story has three degrees of freedom - the horizontal orthogonal translations along the x- and y-directions and the rotation.

Equations of Motion of the Building with TMD

The equations of motion of the building in the presence of seismic forces is

$$[M]\{\ddot{D}\}+[C]\{\dot{D}\}+[K]\{D\}=-[M]\{\ddot{D}_g(t)\}+[H]\{U(t)\} \tag{1}$$

and the equation of motion of the TMD system is

$$[M_0]\{\ddot{D}_0\}+[C_0]\{\dot{\gamma}\}+[K_0]\{\gamma\}=-[M_0]\{\ddot{D}_g(t)\} \tag{2}$$

where the control forces can be expressed as

$$\begin{aligned}\{U(t)\}&=-[M_0](\{\ddot{D}_0\}+\{\ddot{D}_g(t)\})\\&=[K_0](\{D_0\}-\{D_i\})+[C_0](\{\dot{D}_0\}-\{\dot{D}_i\})\end{aligned} \tag{3}$$

where,

$$[M]=diag\big[[m]\quad[m]\quad[J]\big] \qquad [C]=a[M]+b[K] \qquad \{\gamma\}=\{D_0\}-\{D_i\},\{\dot{\gamma}\}=\{\dot{D}_0\}-\{\dot{D}_i\}$$

$$[K]=\begin{bmatrix}[K_{xx}] & [0] & [K_{x\varphi}]\\ [0] & [K_{yy}] & [K_{y\varphi}]\\ [K_{\varphi x}] & [K_{\varphi y}] & [K_{\varphi\varphi}]\end{bmatrix}_{3n\times 3n} \qquad [C]=\begin{bmatrix}[C_{xx}] & [0] & [C_{x\varphi}]\\ [0] & [C_{yy}] & [C_{y\varphi}]\\ [C_{\varphi x}] & [C_{\varphi y}] & [C_{\varphi\varphi}]\end{bmatrix}_{3n\times 3n}$$

$$[C_0]=\begin{bmatrix}c_{dx} & \\ & c_{dy}\end{bmatrix},[K_0]=\begin{bmatrix}k_{dx} & \\ & k_{dy}\end{bmatrix},$$

$$c_{dx}=2m_0w_{dx}\xi_d,k_{dx}=m_0w_{dx}^2,$$

$$c_{dy}=2m_0w_{dy}\xi_d,k_{dy}=m_0w_{dy}^2$$

[H] is the matrix defining the location of TMD, when TMD is setup on the i-th floor,

$$[H]=\begin{bmatrix}0 & \cdots 1 & \cdots\cdots 0 & \cdots l_y\cdots & 0\\ 0 & \cdots 0 & \cdots\cdots 1 & \cdots -l_x\cdots & 0\end{bmatrix}^T_{2\times 3n}$$

$$\begin{matrix}\vdots & \vdots & \vdots\\ i & n+i & 2n+i\end{matrix}$$

$[D_0]$ is displacement vector of the TMD,

$$[D_0]=\{x_0,y_0\}^T$$

$[D_i]$ is the displacements of i-th floor,

$$[D_i]=\{x_i+l_y\cdot\varphi_i,y_i-l_x\cdot\varphi_i\}^T$$

where, l_x and l_y indicate the distances between the floor mass center and the TMD in x and y directions.

Then, the general equations of motion of the building with TMD can be expressed as

$$[M^*]\{\ddot{D}^*\}+[C^*]\{\dot{D}^*\}+[K^*]\{D^*\}=-[M^*]\{\ddot{D}_g^*(t)\} \tag{4}$$

where, $[M^*]$, $[K^*]$ and $[C^*]$ are the combined mass, stiffness and damping matrixes, and $[D^*]$ is the combined displacement vector.

$$[M^*]=diag\big[[m]\quad[m]\quad[J]\quad[M_0]\big] \qquad [K^*]=\begin{bmatrix}[K^*_{xx}] & [0] & [K^*_{x\varphi}] & \\ [0] & [K^*_{yy}] & [K^*_{y\varphi}] & [K_{co}]\\ [K^*_{\varphi x}] & [K^*_{\varphi y}] & [K^*_{\varphi\varphi}] & \\ & [K_{co}]^T & & [K_0]\end{bmatrix}_{(3n+2)\times(3n+2)} \qquad [K_{co}]=-[H][K_0]$$

In which $[K^*_{xx}]$ and $[K^*_{yy}]$ are turn out from $[K_{xx}]$ and $\left[K_{yy}\right]$ by adding k_{dx} and k_{dy} to their i-th diagonal element, respectively. $[K^*_{\varphi\varphi}]$ is turn out from $\left[K_{\varphi\varphi}\right]$ by adding $(l_y^2 k_{dx} + l_x^2 k_{dy})$ to its i-th diagonal element. $[K^*_{x\varphi}]$ and $[K^*_{y\varphi}]$ are turn out from $\left[K_{x\varphi}\right]$ and $[K_{y\varphi}]$ by adding $l_y{}^2 k_{dx}$ and $-l_x{}^2 k_{dy}$ to their i-th diagonal element, respectively. Take $[K^*_{\varphi\varphi}]$ as an example, its formation procedure is shown as

$$\left[K^*_{\varphi\varphi}\right] = \begin{bmatrix} k_{\varphi 11} & -k_{\varphi 12} & & & & & \\ -k_{\varphi 21} & k_{\varphi 22} & -k_{\varphi 23} & & & & \\ & \ddots & \ddots & \ddots & & & \\ & & -k_{\varphi i(i-1)} & k_{\varphi ii} + (l_y^2 k_{dx} + l_x^2 k_{dy}) & -k_{\varphi i(i+1)} & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -k_{\varphi (n-1)(n-2)} & k_{\varphi (n-1)(n-1)} & -k_{\varphi (n-1)n} \\ & & & & -k_{\varphi n(n-1)} & k_{\varphi nn} \end{bmatrix}$$

The combined damping matrix $[C^*]$ follows the same formation of the matrix $[K^*]$.

In the state space, Eq. 4 becomes

$$\dot{Z}(t) = AZ(t) + B\ddot{D}_g^*(t) \tag{5}$$

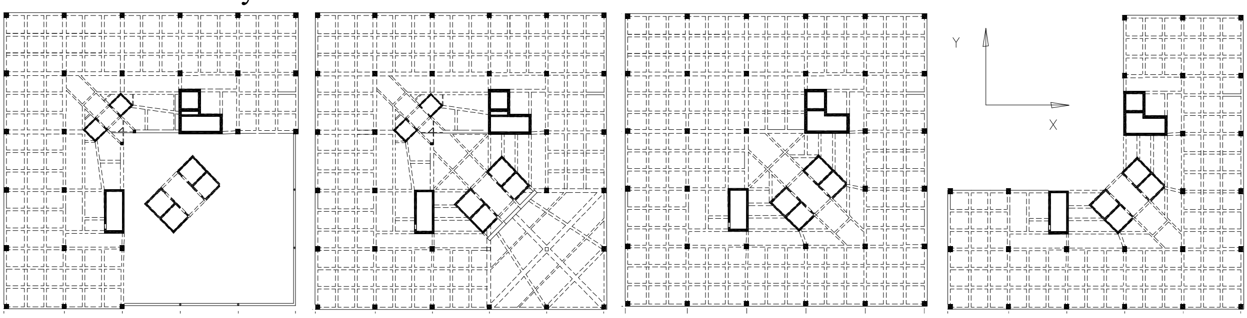
where

$$Z(t) = \begin{bmatrix} D^*(t) \\ \dot{D}^*(t) \end{bmatrix}_{1\times 2(3n+r)} \quad A = \begin{bmatrix} 0 & I_{3n+r} \\ -\left[M^*\right]^{-1}\left[K^*\right] & -\left[M^*\right]^{-1}\left[C^*\right] \end{bmatrix}_{2(3n+r)\times 2(3n+r)} \quad B = \begin{bmatrix} 0 \\ -E \end{bmatrix}_{2(3n+r)\times(3n+r)}$$

$$E = \begin{bmatrix} I_{n\times 1} & 0 & 0_{n\times 1} & 1 & 0 \\ 0 & I_{n\times 1} & 0_{n\times 1} & 0 & 1 \end{bmatrix}^T \quad \ddot{D}_g^* = \begin{bmatrix} \ddot{d}_{gx} \\ \ddot{d}_{gy} \end{bmatrix}$$

Modeling of a High-rising Structure with Large Local Space

A typical high-rising building with large local space [1] is used for verification of the strategy of using bidirectional TMD system to reduce the torsional responses of the structure under seismic excitation. The prototype is a 18-story building with totally height of 98 m, while the height of the first, fourth, ninth and tenth story reach 8.4 m, the height of the top story is 5.8 m and the other story with height of 4.2 m. The plan size of the structure is 44 m×44 m, through deleting some columns of the lowest 4 stories, a 26.3 m×26.3 m large hall is turn out at a corner of the building. Above the tenth floor, some opposite columns are also deleted which forms a series of L- type floors. The general plan layout of the structure is given in Fig. 1. Obviously, the mass and stiffness center of lower and higher part of the structure are far away from the vertical axis.



(a) Floor 1 to 4 (b) Floor 5 (c) Floor 6 to 9 (d) Floor 10 to 18

Fig. 1 Plan layout of the structure

The multi-floor model of the building can be achieved through a response spectrum analysis on its 3-D structural model [5], and the parameters of the established multi-floor model [6] are applied in this research.

The mode analysis is carried out and the period, direction factor and mass participation factor of the first 6 modes are listed in Table 1. The pattern of the first mode is rotation which is exactly in accordance with the test result [1]. One can also find that the rotation component is very remarkable and the rotation factors of mode number 3, 4, 5 and 6 are equal to or greater than 30%. Under earthquake condition, the structure will suffer large torsional displacements.

Table 1 Mode analysis result of the established model

Mode No.	Period (s)	Direction factor			Mass participation factor		
		X	Y	Rotation	X	Y	Rotation
1	2.71	25.5%	23.9%	50.6%	17.9%	15.9%	39.0%
2	2.38	27.4%	68.8%	3.8%	20.1%	50.8%	3.0%
3	2.10	47.4%	7.8%	44.8%	36.8%	6.4%	32.9%
4	0.98	11.7%	58.3%	30.0%	1.3%	9.2%	6.8%
5	0.96	25.9%	41.2%	33.0%	3.3%	7.8%	4.6%
6	0.87	62.7%	0.9%	36.4%	10.1%	0.2%	4.0%

Design of the Bidirectional TMD

According to the plan layout of the building, there are three options to setup the bidirectional TMD system: (1) To hang the TMD at the top of the large local hall - fourth floor; (2) To put the TMD at the vertical layout changing location – ninth floor; or (3) to put the TMD on the top floor of the structure – eighteenth floor. Physically, it is more convenience to choose option (2) and (3), both the tenth floor and eighteenth floor can provide ideal space holding the TMD. From the original objective of reducing the torsion responses of the structure, mainly the torsion responses at the top of the large local hall, option (2) has been chosen and the TMD is set up on the ninth floor.

Generally, the frequency of the TMD system should be set to the main frequency of the controlled structure [7]. For such complex structure, according to the mode analysis result which is listed in Table 1 and the objective of torsion response control, the frequency in x-direction of the TMD system is defined as 0.48 Hz (the frequency of Mode No. 3) while the frequency in y-direction is defined as 0.37 Hz (the frequency of Mode No. 1).

Numerical Result

Based on the equation of motion of the building with TMD of the Eq. 5, a program is developed to assess the effect of the bidirectional TMD system on torsion responses reduction of the seismically excited structure. In order to consider the overall effect of the torsion response reduction under different earthquake waves, a common control ratio is defined as

$$\eta = \sum_{i=1}^{i=n} \eta_i / n \ , \ \eta_i = (U_i^o - U_i^c) / U_i^o$$

where, U_i^o is the maximum response of the un-controlled structure under i-th earthquake wave and U_i^c is the maximum response of the structure with TMD system.

The widely used El Centrol and Talf earthquake records and an artificial earthquake wave are chosen as the input ground accelerations for the numerical analyses. The peak accelerations of the waves are adjusted to 0.2 g. The relationship of the rotation control ratios and the TMD damping ratios with different TMD mass ratio of 0.005, 0.01, 0.015, 0.02, 0.025 and 0.03 are given as Fig. 2. From these diagrams, it is easy to find that the rotation control ratios increase as the TMD mass ratio increase from 0.005 to 0.03. But when the mass ratio is greater than 0.01, the rotation control ratio increase is only about 4% as mass ratio increase of each 0.005. The optimal damping ratio increase as the mass ratio becomes large, and the control effect changes gently when the damping ratio greater than the optimal damping ratio.

As mentioned before, the sample way for determining the TMD parameters is to set its frequencies in both x- and y-direction equaling the first frequency of the structure. The relationship of the rotation control ratios and the TMD damping ratios with different TMD mass ratio of 0.01 and 0.02 are given as Fig. 3. Comparing Fig. 3 with Fig. 2 (b) and (d), one can find the above two modes control strategy is more effective than this first mode strategy.

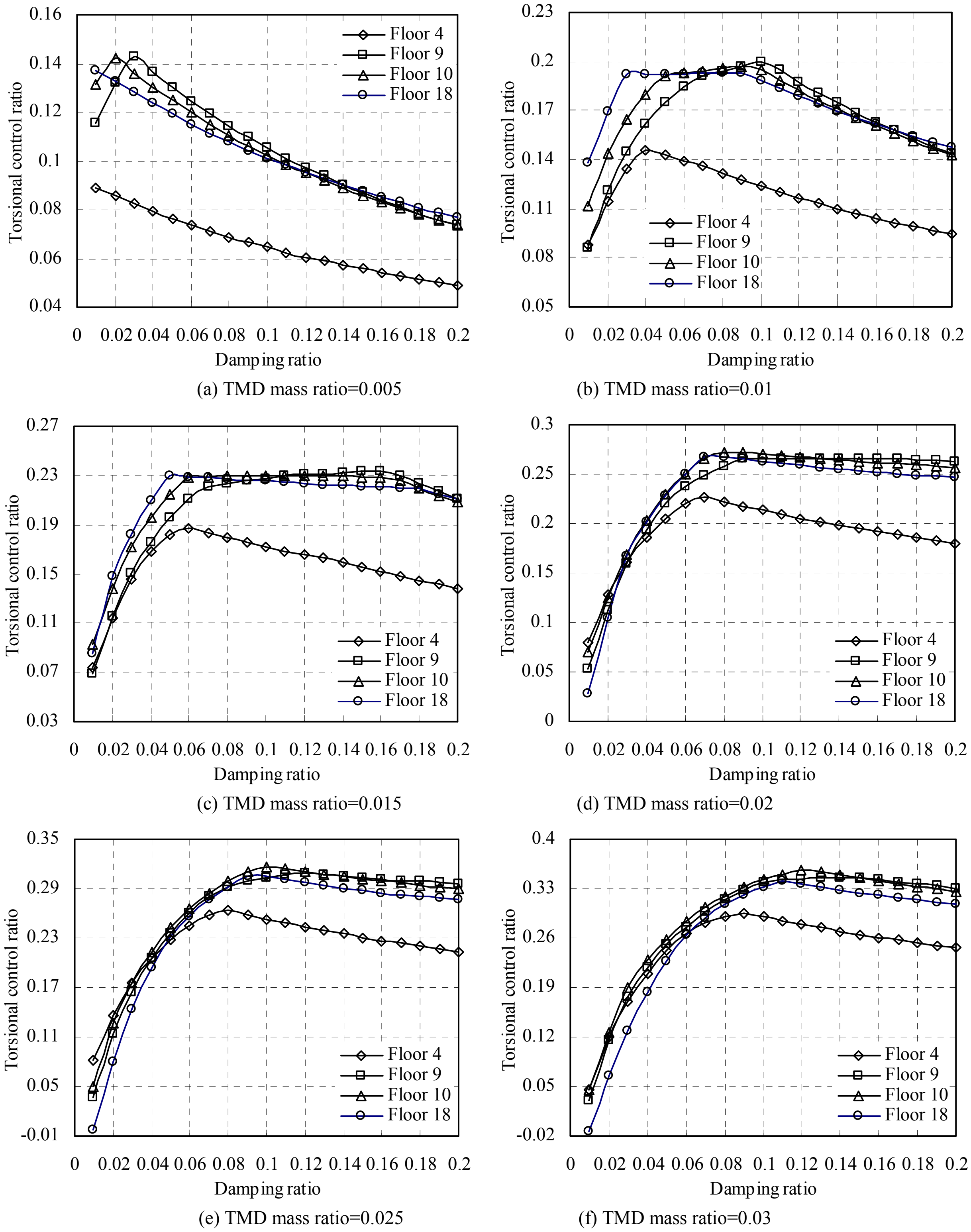


Fig. 2 Relationship between torsional control ratio and damping ratio

Conclusions

In this research, the seismic behavior, mainly the torsional responses and its control strategy, of a complex high-rising building with large local space are studied. The simple multi-floor building model is established and the bidirectional TMD system is applied to reduce the torsional responses of the structure under seismic condition. The numeric analyses indicate that:

(1) A well-designed bidirectional TMD system is very effective in reducing the torsional responses of the whole structure as well as the top of the large local space.

(2) As the complex of the dynamic property of the highly irregular structure like high-rising building with large local space, different dynamic mode should be considered in the TMD parameter design, and an optimal combination of structural modes is more effective than the first mode control strategy.

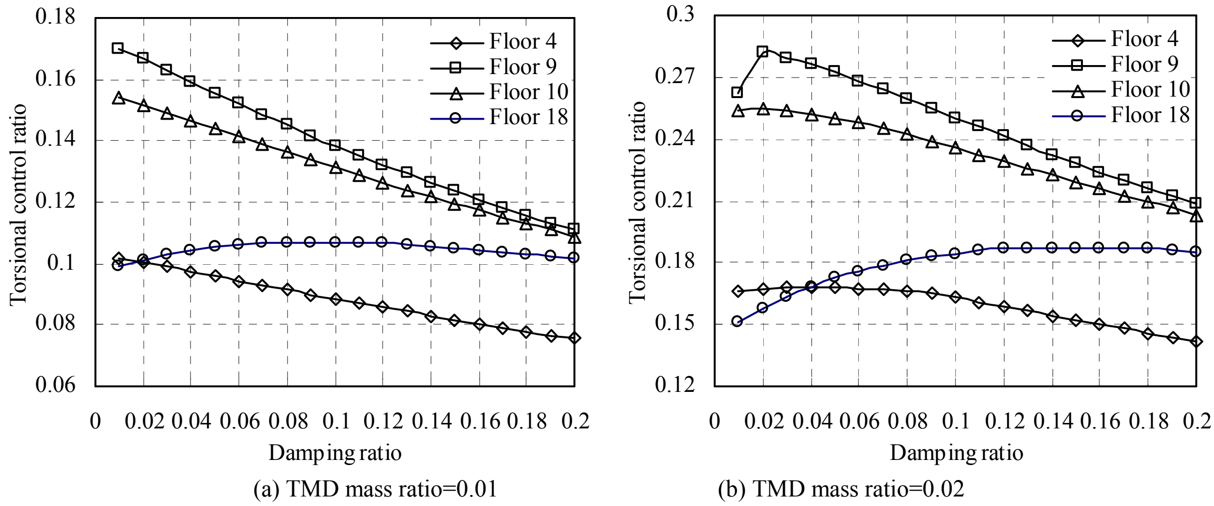


Fig. 3 Relationship between torsional control ratio and damping ratio

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