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Dynamic Analysis on Pool-type Tuned Mass Damper

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Abstract: Presented a pool-type tuned mass damper (TMD), in which the synthetical effects of both tuned liquid damper (TLD) and TMD were considered simultaneously. The equations of motion of the structure with a pool-type TMD, TMD or TLD were formulated. An indoor swimming pool was taken as an example to investigate the control performance of this new pool-type TMD. The control effectivenesses of the pool-type TMD system with various pool-lengths along vibration direction were also computed and compared with that of the corresponding TMD, TLD system under wind or earthquake excitations respectively. The suggestions for designing a pool-type TMD were provided through phase difference analyses. The results show that the optimally designed pool-type TMD can achieve a performance level which is close to that of an ordinary TMD, while both TMDs far outperform TLD. Compared with ordinary TMD, the pool-type TMD has more economical and practical values.

Key words: TMD; TLD; pool-type TMD; vibration control; phase difference

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池式调谐质量阻尼器的动力分析

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摘要:定义了池式调谐质量阻尼器(TMD),运用调谐液体阻尼器(TLD)与 TMD 相结合的方法综合考虑其总体动力效应;同时推导了结构与 TMD、TLD 以及池式 TMD 系统的运动方程。以结构物室内游泳池为例,研究了不同池长设计值的池式 TMD 在风振与地震激励下对结构的控制性能,对比了相应 TMD、TLD 的控制效果,并运用相位差分析的方法对池式 TMD 的设置提出了建议。结果表明:池式 TMD 经优化设计后可取得与普通 TMD 相近的控制效果,均远优于 TLD;同时,池式 TMD 较普通 TMD 更经济且更具实用价值。

关键词:调谐质量阻尼器;调谐液体阻尼器;池式 TMD;振动控制;相位差

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0 Introduction

Tuned mass damper (TMD) has been widely used as a structural passive control device since 1970s[1-5]. TMD is composed of mass, spring and damper, whose acting mechanism is that when a structure vibrates due to external excitations, TMD will be driven to move in the opposing direction, and the inertia force of TMD produced by the relative movement will be tuned to retroact on the structure to reduce the structural responses[6]. The tuned mass can be made of metal, concrete or even is provided by additional facilities of a structure, such as storage water tank, indoor swimming pool, helipad, etc. At present, using additional facilities of a structure as the tuned mass, it becomes a tendency under the consideration of practicability and economy of design[7]. There are some successful examples of engineering application over the world. Centerpoint Tower is a very famous landmark in Australia, in which the storage tank used for both water supply and fireproofing is designed to be the mass of TMD. The storage water tank in the top floor of Crystal Tower in Japan is also used as tuned mass of TMD. Recently, the helipad in the roof of Hankyu Chayamachi Edifice in Japan is a large TMD[8]. Storage water tank is also designed to control the structural vibration both in Shantou TV Tower and Shanghai Jiading TV Tower[9]. In addition, platform modules and heavy-duty equipments are often refitted to be TMDs in offshore platforms[10]. A swimming pool in the roof of a hotel under construction in Shanghai is devised as the TMD to reduce structural vibration.

A pool-type TMD proposed in this paper means that a pool or an underfilled water tank is designed to be the additional mass of a TMD, in which the dynamic effect of sloshing water is considered on the basis of TMD. When the structure shakes due to wind or earthquake, the sloshing water in the pool or tank affects the performance of the whole tuned damper system (pool-type TMD), which can not be neglected. As a result, the pool-type TMD shows the synthetical effect of both the TMD and TLD, and differs from that of a solid-type TMD with the same mass. In practical engineering, people always estimate the difference in control effectiveness between pool-type TMD and TMD with the same mass just by experience, which is imprecise and limitative and can not offer the results accurately with various container sizes or changed water depth of the pool-type TMD. In view of this, the theories of TLD and TMD are combined together to synthetically analyze the total dynamic effect of tuned damper system in this paper. A minitype indoor swimming pool is taken as an example to investigate the control performance of this new pool-type TMD. Comparison of performance between TMD and pool-type TMD is made under wind and earthquake excitations respectively. The effect of various pool-lengths along vibration direction on control performance is discussed and then suggestions for designing a pool-type TMD are provided for a wide application of the new type TMD in the real engineering.

1 Dynamic Model of TMD and Pool-type TMD

The only difference between pool-type TMD and TMD is that the dynamic effect of water must be considered in pool-type TMD while TMD needn't consider it. Fig. 1 shows the models of pool-type TMD and TMD respectively. As shown in Fig. 1, M_s, C_s, K_s are the mass, damping and stiffness of the SDOF structure respectively; M_{TMD}, C_{TMD} and K_{TMD} are the mass, damping and stiffness of TMD respectively; M_1 and M_2 are the container mass and liquid mass in pool-type TMD system; C_{PTMD} and K_{PTMD} are the damping and stiffness of pool-type TMD system. Moreover, the indoor swimming pool is rectangular, with which domestic water (ρ=1 000 kg · m^{-3}) is filled.

2 Basic Theory of TLD System

TLD is also a widely used passive control device, which is composed of water filled tanks with the sloshing frequency tuned to the natural frequency of the controlled structure. The equivalent

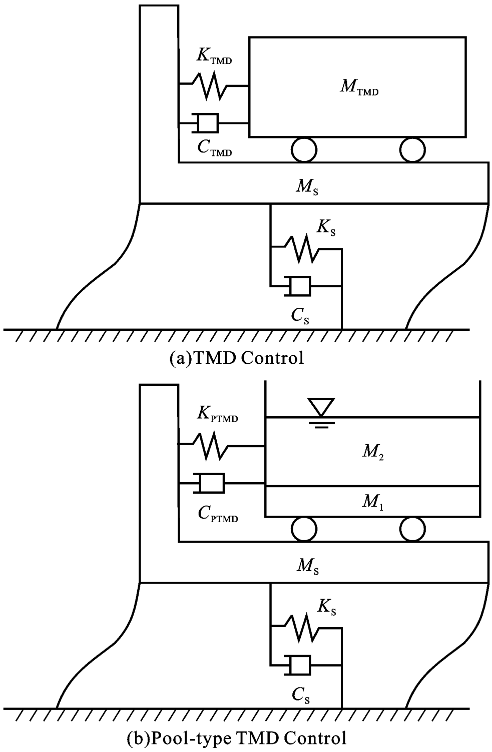

Fig. 1　Dynamic Model of SDOF Controlled Structure

图 1　单自由度受控结构动力模型

sloshing mass, fixed mass and stiffness of water in tank are obtained according to the procedure proposed by Housner[11], as shown in the following

$$M_{SL}=0.83M_W\tanh(3.2h/a)/(3.2h/a) \quad (1)$$

$$M_F=M_W\tanh(0.86a/h)/(0.86a/h) \quad (2)$$

$$K_{TLD}=12ghM_{SL}^2/(M_W a^2) \quad (3)$$

where M_W is the total water mass of TLD; a is the tank length along the vibration direction; h is the water depth in tank, while g is gravitational acceleration. In addition, filter screens are not considered to set in water tank in this paper, thus the damping ratio of sloshing water can be assumed as $\xi=0.05$.

Equation of frequency for the first sloshing mode of water[12] can be expressed as follows

$$\omega=\sqrt{(g\pi/a)\tanh(\pi h/a)} \quad (4)$$

From Eq. (4), one can obtain the sloshing frequency of water in the condition that a and h are given.

Fig. 2 shows the relationship between water depth and sloshing frequency for different tank lengths. The dynamic characteristics of TLD are varied with container length a and liquid depth h. One can see from Fig. 2 that the greater the water

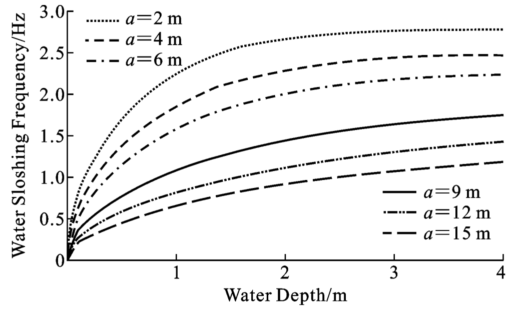

Fig. 2　Relationship Between Water Depth and Sloshing Frequency for Different Tank Lengths

图 2　不同水箱长度下液体深度与液体晃动频率的关系

depth is, the higher the sloshing frequency is. When the water depth in tank increases to a certain level, the sloshing frequency tends to a constant. Hence, the TLD should be designed optimally to achieve a desired level of control performance.

3　Formulation

3.1　Equations of Motion of TMD and TLD

Eqs. (5) and (6) are the equations of motion of structure－TMD system in case of wind and earthquake excitations respectively.

$$M_{TMD}\ddot{Z}+C_{TMD}(\dot{Z}-\dot{Z}_S)+K_{TMD}(Z-Z_S)=0 \quad (5)$$

$$M_{TMD}\ddot{Z}'+C_{TMD}(\dot{Z}'-\dot{Z}'_S)+K_{TMD}(Z'-Z'_S)=-M_{TMD}\ddot{Z}_a \quad (6)$$

where M_{TMD}, C_{TMD} and K_{TMD} are the mass, damping and stiffness of TMD as defined before; $\ddot{Z}$, $\dot{Z}$ and Z are the horizontal accelerations, velocity and displacement of the TMD under wind excitations respectively; $\dot{Z}_S$ and Z_S are the horizontal velocity and displacement of the structure under wind excitations respectively; $\ddot{Z}'$, $\dot{Z}'$, Z', $\dot{Z}'_S$ and Z'_S are the corresponding values under earthquake excitations respectively; $\ddot{Z}_a$ is the ground acceleration.

If a TLD is installed on a SDOF structure similar to the case of TMD, the motion equations of structure－TLD system under wind or earthquake excitations are given by Eqs. (7) and (8)

$$M_{SL}\ddot{Y}+C_{TLD}(\dot{Y}-\dot{Y}_S)+K_{TLD}(Y-Y_S)=0 \quad (7)$$

$$M_{SL}\ddot{Y}'+C_{TLD}(\dot{Y}'-\dot{Y}'_S)+K_{TLD}(Y'-Y'_S)=-M_{TLD}\ddot{Y}_a \quad (8)$$

where M_{SL} is the sloshing mass of water; C_{TLD} and K_{TLD} are the damping and stiffness of TLD respectively; $\ddot{Y}$, $\dot{Y}$ and Y are the horizontal acceleration, velocity and displacement of the sloshing water under wind excitations respectively; $\dot{Y}_S$ and Y_S are the horizontal velocity and displacement of the structure under wind excitations respectively; $\ddot{Y}'$, $\dot{Y}'$, Y', $\dot{Y}'_S$ and Y'_S are the corresponding values under earthquake excitations; $\ddot{Y}_a$ is the ground acceleration.

3.2 Motion Equations of Structure with Pool-type TMD

According to the analytical model shown in Fig. 1(b), the motion equations of structure with pool-type TMD system under wind or earthquake excitations can be expressed as follows

$$M_S\ddot{X}+C_S\dot{X}+K_SX=p-f_C \tag{9}$$

$$M_S\ddot{X}'+C_S\dot{X}'+K_SX'=M_S\ddot{X}_a-f'_C \tag{10}$$

where M_S, C_S and K_S are the mass, damping and stiffness of the structure as defined before; $\ddot{X}$, $\dot{X}$ and X are the horizontal acceleration, velocity and displacement of the structure under wind excitations respectively; p and f_C are the wind force and the control force on the structure provided by pool-type TMD respectively; $\ddot{X}'$, $\dot{X}'$ and X' are the horizontal acceleration, velocity and displacement of the structure under earthquake excitations respectively; $\ddot{X}_a$ is the ground surface acceleration; f'_C is the control force on the structure provided by pool-type TMD under earthquake excitations. Combined with Eqs. (5), (7) and (9), the motion equations of the structure with pool-type TMD system under wind excitations can be rewritten in matrix form

$$\boldsymbol{M}\ddot{\boldsymbol{X}}+\boldsymbol{C}\dot{\boldsymbol{X}}+\boldsymbol{K}\boldsymbol{X}=\boldsymbol{P} \tag{11}$$

Similarly, combined with Eqs. (6), (8) and (10), the motion equations of the structure with pool-type TMD system under earthquake excitations can also be written in matrix form as follows

$$\boldsymbol{M}\ddot{\boldsymbol{X}}'+\boldsymbol{C}\dot{\boldsymbol{X}}'+\boldsymbol{K}\boldsymbol{X}'=-\boldsymbol{M}\ddot{\boldsymbol{X}}_a \tag{12}$$

where $\ddot{\boldsymbol{X}}$, $\dot{\boldsymbol{X}}$ and $\boldsymbol{X}$ are the horizontal acceleration vector, velocity vector and displacement vector of the structure-pool-type TMD system under wind excitations; $\ddot{\boldsymbol{X}}'$, $\dot{\boldsymbol{X}}'$ and $\boldsymbol{X}'$ are the corresponding values under earthquake excitations; $\boldsymbol{P}$ is the external wind excitation vector; $\ddot{\boldsymbol{X}}_a$ is the ground surface acceleration vector. The mass matrix $\boldsymbol{M}$, the damping matrix $\boldsymbol{C}$ and the stiffness matrix $\boldsymbol{K}$ of the structure with pool-type TMD system can be expressed as follows

$$\left.\begin{aligned}
\boldsymbol{M}&=\begin{bmatrix} M_S & 0 & 0 \\ 0 & M_1+M_2 & 0 \\ 0 & 0 & M_{SL} \end{bmatrix}\\
\boldsymbol{C}&=\begin{bmatrix} C_S+C_{TMD} & -C_{TMD} & 0 \\ -C_{TMD} & C_{TMD}+C_{TLD} & -C_{TLD} \\ 0 & -C_{TLD} & C_{TLD} \end{bmatrix}\\
\boldsymbol{K}&=\begin{bmatrix} K_S+K_{TMD} & -K_{TMD} & 0 \\ -K_{TMD} & K_{TMD}+K_{TLD} & -K_{TLD} \\ 0 & -K_{TLD} & K_{TLD} \end{bmatrix}
\end{aligned}\right\} \tag{13}$$

4 Numerical Simulation

Referring to the numerical example used by Haroun et al[13], the structural parameters are given: $M=3.800\times10^6$ kg, $K=2.979\times10^7$ N·m^{-1} ($\omega_0=2.800$ rad·s^{-1}), $C=3.50\times10^5$ N·s·m^{-1}. To be brief, simulation of external wind load is $p=1\times10^5 e^{-j\omega t}$ N, while the simulation of earthquake excitation also uses sinusoidal wave with the peak acceleration of 5 gal. The ratio of pool-type TMD mass to structure mass is assumed to be $\mu=0.03$ and the total mass of the pool-type TMD is: $M_1+M_2=114\ 000$ kg, in which the solid mass M_1 is 30 000 kg. Moreover, water depth in the swimming pool is designed to be 1.5 m.

Tab. 1 and Tab. 2 compare the control effectiveness of pool-type TMD, TMD and TLD under wind and earthquake excitations respectively. It can be observed from Tab. 1 and Tab. 2 that pool-type TMD shows the similar dynamic characteristics under wind and earthquake excitations. That is, when a is 2～6 m, the peak values of responses of the structure controlled by pool-type TMD are much higher than that controlled by TMD, especially in the case of $a=4$ m, the maximal responses are close to those of the uncontrolled structure. When the pool length is very high, the peak values of responses of the structure with the pool-type TMD converge to those with the ordinary TMD and both far outperform the TLD. The results show that the pool-type TMD is a good choice in practical engineering applications because of its ef-

Tab. 1 Peak Values of Responses of Pool-type TMD Controlled Structure with Different Pool Lengths Under Wind Excitations

表 1 风振下不同池长的池式 TMD 控制的结构峰值响应

Conditions	Uncontrolled	TMD Controls	TLD Controls	Pool Length a/m								
				1	2	3	4	5	6	9	12	15
Displacement/cm	10.21	2.57	4.21	3.20	4.95	6.75	7.77	7.36	6.17	3.86	3.11	2.78
Acceleration/(m·s^{-2})	0.80	0.19	0.33	0.27	0.41	0.55	0.62	0.57	0.47	0.27	0.21	0.20

Tab. 2 Peak Values of Responses of Pool-type TMD Controlled Structure with Different Pool Length Under Earthquake Excitations

表 2 地震下不同池长的池式 TMD 控制的结构峰值响应

Conditions	Uncontrolled	TMD Controls	TLD Controls	Pool Length a/m								
				1	2	3	4	5	6	9	12	15
Displacement/cm	19.39	4.54	7.62	5.73	8.90	12.38	14.57	14.11	12.07	7.27	5.93	5.33
Acceleration/(m·s^{-2})	1.52	0.35	0.59	0.47	0.73	0.98	1.16	1.09	0.90	0.57	0.43	0.40

ficiency and economy.

The phase differences between sloshing water and TMD system under wind and earthquake excitations are shown in Fig. 3. It can be observed from Fig. 3 that when the frequency of sloshing water ω_{SL} is close to ω_0 and within the frequency ranges between ω_1(2.600 rad·s^{-1}) and ω_2(3.100 rad·s^{-1}), phase differences between sloshing water and TMD range from 30° to 150°, this region can be defined as hard-vibration area (HVA). When ω_{SL} is in and near HVA (a is 2～6 m), the dynamic effect of sloshing water affects the performance of the pool-type TMD system greatly, especially for $\omega_{SL}=\omega_0$ ($a\approx 3.5$ m, $\Phi=90°$), the whole sloshing water completely restrains the TMD system as TMD restrains the structure which means the worst control effect of pool-type TMD is obtained. On the other hand, when ω_{SL} is far away from HVA and Φ goes to 0° (in phase differences), better control effectiveness is achieved, especially for $a=15$ m, the dynamic effect of sloshing water affects the pool-type TMD system slightly which means control effectiveness of the system can be guaranteed. It indicates that the greater a is, the better control performance can be achieved. In addition, when ω_{SL} is far away from HVA and Φ is greater than 150° but not closes to 180°; the control effectiveness is still not so good as compared with the case when Φ goes to 0°. Notice that a phase step happens for $150°<\Phi<180°$ as shown in Fig. 3(b), which means that a confusion of phase differences between sloshing water and TMD system exhibits in this region when the structure is under earthquake excitations. In other words, it is not advisable to select $a<3$ m as the pool length in the case of earthquake excitations. Furthermore, the dimensions (length and width) of an indoor swimming pool should be within the range of 5～15 m in real engineering structures. Hence, $a=11.2$ m is an optimal pool length in this numerical example.

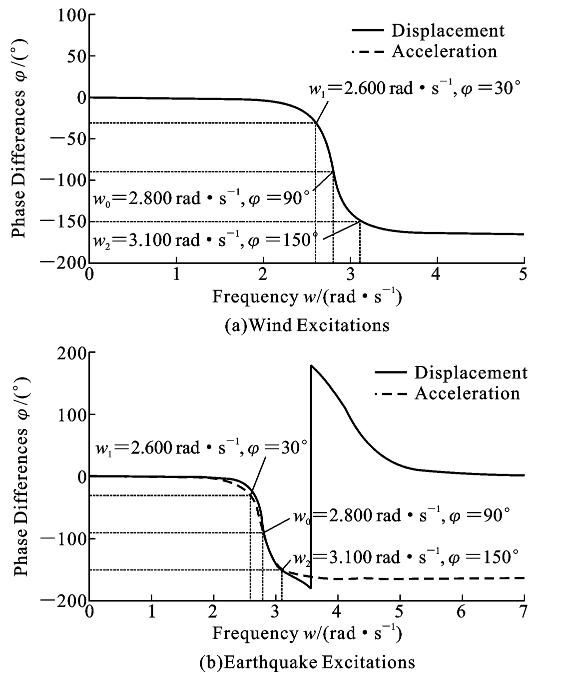

Fig. 3 Relation Between Sloshing Water Frequency in Pool-type TMD and Response Phase Differences of Sloshing Water and TMD

图 3 池式 TMD 中晃动水与 TMD 的响应相位差对应晃动频率的关系

5 Conclusions

(1) Water storage equipments are often designed as the mass of TMD. However, the sloshing water adversely affects the control performance of TMD, which can not be neglected. Traditional estimation is imprecise and can not be used widely. The proposed method combining the theories of TLD and TMD to analyze the total dynamic effect of the pool-type TMD system is feasible.

(2) A SDOF structure under both wind and earthquake excitations is discussed. The results of phase difference analyses indicate that the worst control effectiveness of pool-type TMD happens in and near HVA and better control performance can be achieved in the region far away from HVA. The calculations show that the pool length along the vibration direction should be chosen as larger as possible to make sloshing water and TMD system move in phase, and then a pool-type TMD achieves the best performance.

(3) The control effectiveness of a pool-type TMD is much better than that of a TLD and close to that of a TMD when the pool size is reasonably designed. Compared with ordinary TMD, the pool-type TMD has more economical and practical values. The pool-type TMD systems show diverse design for tuned-type systems.

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