



# Development of semi-active mass damper with impulsive reaction

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**Abstract.** A new semi-active mass damper, included active joint to control Lock/Unlock between the mass of damper and structure, is proposed to avoid “de-tuning effect” in this study. A ten-floor shear building with Tuned Mass Damper (TMD) and Semi-Active Mass Damper (SAMD) under excitation of 26 earthquake records is simulated by numerical analysis to compare the shock absorption effects. Analysis results show that: (1) Shock absorption of roof displacement and root mean square (RMS) roof displacement is 9.9%, 15.8% and 67.9%, 70.9% for structure with TMD and SAMD under excitation of Kobe 1995 earthquake respectively. Shock absorption of roof displacement and RMS roof displacement 52.7%, 62.1% and 55.7%, 66.3% for structure with TMD and SAMD under excitation of Sumatra 2007 earthquake respectively. (2) Structural response of building with SAMD controlled is very low sensitivity to frequency ratio. SAMD control effect is better than that of TMD on near fault earthquakes and suitable for far-field earthquakes. Otherwise, SAMD is almost without “de-tuning effect”. (3) Shock absorption ratio of the roof displacement responses and RMS displacement responses for structure with SAMD under excitation of far-field earthquake is above 38% and 62%, respectively. The frequency ratio of SAMD controlled should be limited to less than 4.0 to avoid enlarging the maximum acceleration responses. The practicability of this proposed SAMD has been verified by numerical analysis.

**Keywords.** Active joint; tuned mass damper; TMD; semi-active mass damper; SAMD; de-tuning effect; high-rise building.

## 1. Introduction

Dynamic responses of slender soft structures, such as high-rise buildings, telecommunication towers, towers, wind generator towers, under dynamic loads can cause loss of function or structural damage. Effective shock absorbers can raise safety and practicality of structure. Existing shock absorbers can be roughly divided into two major technological types: added damping type of damper and base isolation. Added damping type is suitable for high-rise building and wind-resistant structure. Mass damper is the first practice technique for wind-resistant and earthquake-resistant structure. Otherwise, this technique is also one of the most significant seismic proof ways for high-rise building. Two famous application examples in Taiwan are Taipei 101 with Tuned Mass Damper (TMD) [1] and 85 Sky Tower in Kaohsiung with Active Mass Damper [2].

Traditional Tuned Mass Damper [3], can be divided into four categories [4] and also can be applied as multiple TMD [5], consists of mass block, spring and damping. Weight of mass block is 1% of total weight of structure.

TMD should be installed inside the superstructure. Design frequency of TMD is close to the natural frequency of structure, TMD produces a reverse resonance behavior when structure under excitation of external force. TMD increased the amount of vibration to reduce structural dynamic responses. The incoming external energy of structure is vanished through damping of TMD. There are many well-known practical application cases in the high-rise buildings of the world, such as: Citigroup Center, New York, USA [6], CN Tower, Toronto, Canada [7] and John Hancock Tower, Boston USA [8]. The main function of TMD is to reduced 30% to 40% vibration, induced by wind force. Some practical application cases, experimental test and numerical analysis results [9–11] verified these control effects. There are two main defects of TMD [12–14]: (1) de-tuning effect: if natural frequency estimation and actual frequency of main structure is incorrect, the design frequency of TMD is not the optimal frequency. These small errors between estimation and actual frequency cause “de-tuning effect”, greatly reducing seismic proof effect of TMD; (2) large displacement: structural displacement scope of main building is limited, when the displacement goes out of scope, TMD is not practical.

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Developing new technique for shock absorption to avoid de-tuning effect is the main research objective in this study. Switch controller is applied to “LOCK” and “UNLOCK” between main structure and mass block of damper. These semi-active technologies such as accumulated semi-active hydraulic damper (ASHD) [15], magnetorheological (MR) fluid dampers, semi-active stiffness dampers, semi-active tuned liquid column dampers, and piezoelectric dampers [16, 17], an improved displacement semi-active hydraulic damper (DSHD) [18] and the semi-active control law, based on the one step ahead prediction of the structural responses [19] compared to active control technology, such as the fourth-order Runge–Kutta method and instantaneous optimal control method are applied to the active control system [20] and the active control based on the output vector prediction [21], does not need large energy to operate equipment. This technology can reduce the active control risk of being unable to play seismic proof effect for power failure, induced by earthquake and strong typhoon or hurricane.

In this study, a new Semi-Active Mass Damper, SAMD is proposed to improve the defects of TMD. An active joint is installed in this new SAMD to control Lock/Unlock between the mass of damper and structure. A parameter study of this SAMD displays the optimal design parameters of this SAMD are frequency ratio around 4 with mass ratio around 0.004–0.006 [22]. In order to investigate the control performance of this proposed SAMD, a ten-floor shear building with traditional TMD and SAMD are simulated by numerical analysis to compare the shock absorption effects. Otherwise, structural control effects for building with these two passive dampers excited by 26 earthquake records with near-fault and far-field earthquake records to compare the practicability of these two dampers. Therefore, four Indices of control performance (1) the average value of ratio of the maximum roof displacement responses; (2) the average value of ratio of root mean square of roof displacement responses; (3) the average value of ratio of the absolute maximum roof acceleration responses and (4) the average value of ratio of the maximum displacement responses of control mass block are defined to evaluate and compare the control effect of building with TMD and SAMD.

## 2. Concept of semi-active mass damper with impulsive reaction

The main concept of semi-active mass damper is that an active joint can control Lock/Unlock between the mass of damper and structure to form series system of structure-spring-active joint-mass of damper, shown in figure 1. The symbol  $\oplus$  in figure 1(a) represents active joint that can use fast electromagnetic server or solenoid valve to execute Lock/Unlock switch. Unlock of active joint is shown in figure 1(b). There is no interaction with mass block of damper and structure or weak stiffness of spring and energy

dissipator to maintain weak interaction force to reduce stroke of mass block. Conversely, Lock of active joint is shown in figure 1(c). Strong spring is connected between mass block and main structure to cause interaction force to change the movements of structure and mass block based on the deformation of strong spring. Inertial forces of mass block of damper act positive work to separate spring and mass block of damper and operate negative work to link spring and mass block of damper. Therefore, this damper only does negative work on structure and ensures to perform the similar effect as the phase difference of 90 degrees.

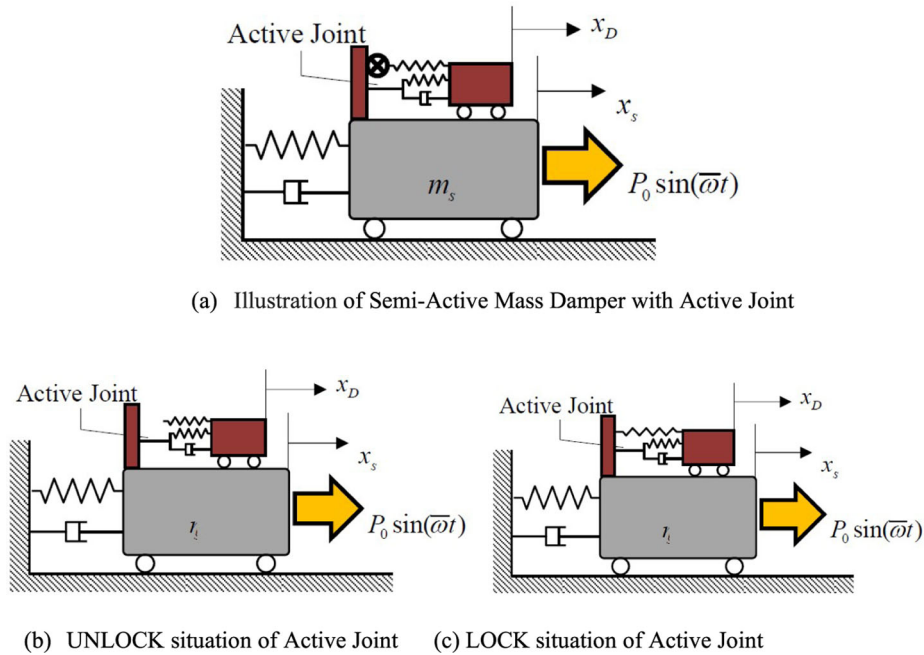
The difference between spring, controlled by active joint, and spring of traditional semi-active tuned mass damper is that spring constant of figure 1 is much larger than spring, the frequency ratio equal to 1. That is, when status of active joint is “LOCK”, frequency of mass block is 2 to 10 times of structure frequency. If there is relative movement speed between mass of main structure and mass block of damper at LOCK status of active joint, active joint switches to “UNLOCK” status suddenly to produce “push force” or “pull force” according to instantaneous deformation of spring. The moving direction of relative velocity between main structure and mass block of damper is switched at short time to cause impulsive changes of action force because that the frequency of mass damper is much larger than that of main structure. Switching time of active joint, based on plus-minus sign of mass block works on main structure, the decisions are as follows: inertial force of mass of damper acts positive work on structure, separation connection between spring and mass of damper, active joint switches to “UNLOCK”. If the inertial force of mass of damper acts negative work on structure, active joint switches to “LOCK” to combine the spring of structure and mass of damper. Therefore, this mechanism can ensure this kind damper to perform only negative work to structure.

## 3. Control law

Control law of this proposed semi-active mass damper is described as follows:

1. If the status of active joint is “UNLOCK”, then  $(W_V V_S - W_A A_S) \times V_{CS} \leq 0$ , the status of active joint would be switched to “LOCK”.
2. If the status of active joint is “LOCK”, then  $V_S \times D_{CS} > 0$ , the status of active joint would be switched to “UNLOCK”.

where,  $V_S$  is the movement speed of structure under controlled, that is movement speed of main structure. Assume rightward is positive;  $A_S$  is the motion acceleration and assume rightward is positive;  $V_{CS}$  is the movement speed of control mass block, relative to the movement speed of controlled structure and assume rightward is positive;  $D_{CS}$  is the displacement of control mass block at active joint



**Figure 1.** Diagrammatic sketch of Impact Semi-Active Mass Damper.

switched to “LOCK” relative to that of control structure is equal to the deformation of switch spring;  $V_S \times D_{CS} > 0$  represents that semi-active mass damper acts positive work to structure.  $W_V$  is speed weight, it is constant, greater or equal to 0.  $W_A$  is acceleration weight, it is constant, greater or equal to 0. Figure 2 reveals time history of structural displacement and control force of structure added with SAMD. Main structure is single degree of freedom. Parameters of SAMD set as frequency ratio = 4.0,  $W_V : W_A = 0 : 1$ . Action of active joint is decided by the sign of structural acceleration responses. Structural responses are simulated by the structure added with SAMD under excitation of Kobe earthquake.

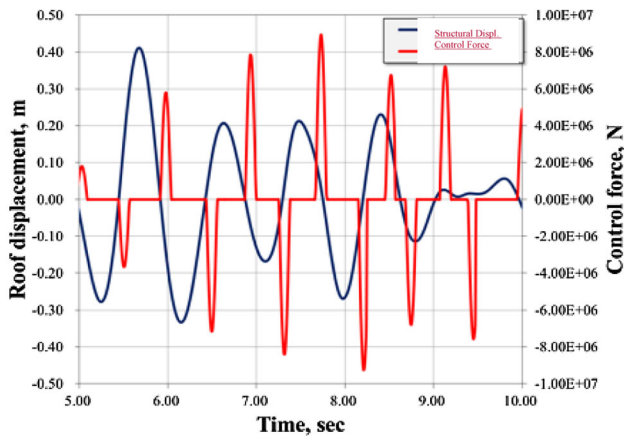
Figure 2 shows that when sign of structural displacement changes from negative to plus or alter from plus to negative, it is positive and negative of acceleration changes. Activities of active joint do a grasp of the joint action. Then, the action direction of control force turns away and with the same movement direction of structural speed to “UNLOCK” of control mass block. This action avoids that SAMD acts positive work to structure successfully.

#### 4. Case study

In this study, numerical analysis method is applied to analyze the roof displacement responses of shear building and dynamic responses of control mass block under structural control of Tuned Mass Damper, TMD and Semi-Active Mass Damper, SAMD subjected to earthquake excitation. The comparison of structural displacement responses of structure under control of different damper with various parameter combinations and shock absorption ratio of displacement responses of control mass block are discussed. Then, the influence of Near-Fault and Far-Field earthquakes on structural control effects are compared in this study.

##### 4.1 Analyze setting

In order to compare the control characteristics between this proposed SAMD and TMD, structural responses of a ten-floor shear building added with SAMD or TMD, shown in figure 3, are analyzed the structure under excitation of



**Figure 2.** Typical time history of control force and structural displacement responses of structure added with proposed SAMD.

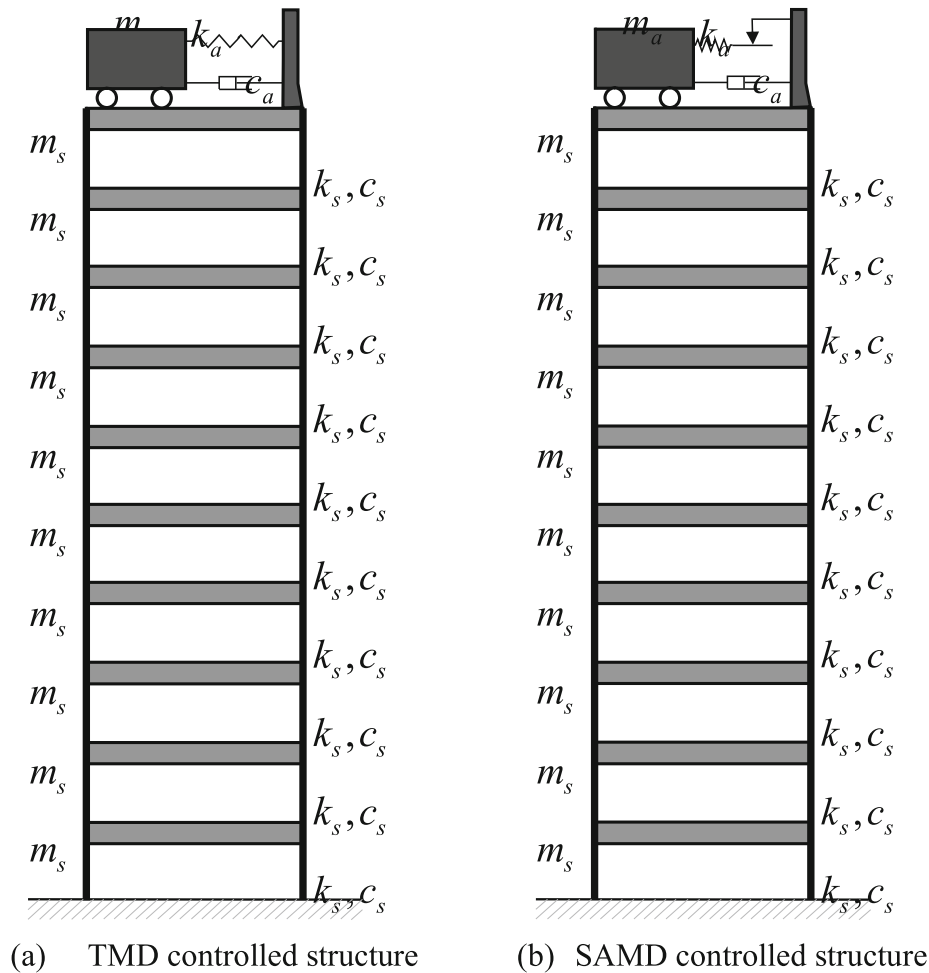


Figure 3. Structure and mass damper model in study.

various seismic wave. Parameters of main structure, control parameters of SAMD and TMD are described as follows:

4.1a *Parameters for main structure:* Bare structure is a ten-floor shear building with mat foundation, depth = 10 m. Construction material of this analysis building is reinforced concrete. Assume mass for each floor is 200 tons, story stiffness ( $k_a$ ) and damping coefficient ( $c_a$ ) are 883,645 kN/m and 2813kN s/m respectively. Frequency of the 1st mode ( $f_0$ ) and damping ratio ( $\xi_0$ ) are 1.0 Hz and 0.01, respectively.

4.1b *Control parameters for SAMD:* Control parameters for SAMD can be divided into two categories: (1) control parameters for systematic hardware: ratio of control mass block ( $\mu$ ), frequency ratio of control mass block ( $\gamma_f$ ) and damping ratio of control mass block ( $\xi_a$ ); (2) Control parameters for control law: speed weight ( $W_V$ ) and acceleration weight ( $W_A$ ) for control law. Analysis parameters setting are Mass ratio:  $\mu = 0.04$ , Freq. ratio:  $\gamma_f = 1.0 \sim 6.00$  @ rate = 0.95, Mass Damping ratio:  $\xi_a = 0.071$ .

Ratio of control mass block can be defined as the ratio (mass of control block)/ (mass of main structure):

$$\mu = \frac{m_d}{\sum m_s} \tag{1}$$

Frequency ratio of control mass block is defined as the ratio (natural frequency of control mass block)/ (frequency of the 1<sup>st</sup> mode of main structure):

$$\gamma_f = \frac{f_a}{f_0} = \frac{\sqrt{k_a/m_a}}{2\pi f_0} \tag{2}$$

Ratio of speed weight ( $W_V$ ) and acceleration weight ( $W_A$ ) in control law affects the switch timing for “UNLOCK” status to “LOCK” status between control mass block and main structure. If  $W_V : W_A = 1 : 0$ , Switch timing of SAMD depends on structural speed at the installation position of control mass block to decide switch timing. It causes that combination timing for SAMD and structure is at the timing point of reverse movement direction of structure. That is at the maximum/minimum

structural displacement when structural velocity is zero. As regards the middle ratio of these two extreme states, switch timing occurs between these two values at timing of the same direction of structural velocity and acceleration. Therefore, weight ratio sets as  $(W_V/W_A) = \omega_0/1$  to discuss structural responses and shock absorption effects.

**4.1c Control Parameters of TMD:** Control parameters of TMD is mass ratio of control block  $\mu$ , frequency ratio of control block  $\gamma_f$  and damping ratio of control mass block  $\xi_a$ . All definition of parameters are the same as those of SAMD. In order to compare the influence of shock absorption effect by detecting effect, frequency ratio of control block  $\gamma_f$  will be changed. Range of frequency ratio of control block  $\gamma_f$  is  $0.8145 \sim 1.9480$ @rate = 0.95. Therefore, the definition of detecting ratio  $\Delta\gamma_f$  is ratio of the difference of frequency of control mass block and the optimal frequency ratio of TMD to the optimal frequency ratio of TMD, as follows:

$$\Gamma = \frac{\gamma_f - \gamma_{f,opt}}{\gamma_{f,opt}} \times 100\% \quad (3)$$

Analysis parameters setting are Mass ratio:  $\mu = 0.04$ , Freq. ratio:  $\gamma_f = 0.8145 \sim 1.9480$ @rate = 0.95, Damping ratio:  $\xi_a = 0.071$ , Detuning rate:  $\Gamma = 18.55\% \sim 22.77\%$ .

To acquire the influence of Near-Fault and Far-Field earthquakes on structural control effects, bare structure, structure added with TMD and SAMD are subjected to 26 earthquake records, listed in Table 1. The distance between the seismic stations of the first five earthquake records and earthquake epicenters within twenty kilometers are defined as Near-Fault earthquakes and the following twenty-one earthquakes are more than twenty kilometers from the seismic station to earthquake epicenters are defined as Far-Field earthquakes. In this paper, the analysis of the building with control and without control under these seismic disturbances are calculated to find the statistical values of the maximum displacement responses of the top floor, the root mean square of the top floor displacement, the maximum acceleration responses of the top floor, and the maximum displacement responses of the mass block, in order to investigate the de-tuning phenomenon and the distance of earthquake epicenter on the control effect of SAMD. All analysis setting value of this study is listed in table 1.

## 4.2 Control performance valuation

In order to evaluate the control effect of SAMD, four Indices of control performance are defined as follows:

- (1) The average value of ratio of the maximum roof displacement responses:  $J_1$

$$J_1 = average \left( \frac{\max(|Roof\ displacement\ with\ SAMD\ or\ TMD|)}{\max(|Roof\ displacement\ without\ control|)} \right) \quad (4)$$

- (2) The average value of ratio of root mean square of roof displacement responses:  $J_3$

$$J_3 = average \left( \frac{rms(Roof\ displacement\ with\ SAMD\ or\ TMD)}{rms(Roof\ displacement\ without\ control)} \right) \quad (5)$$

- (3) The average value of ratio of the absolute maximum roof acceleration responses:  $J_5$

$$J_5 = average \left( \frac{\max(Roof\ acceleration\ with\ SAMD\ or\ TMD)}{\max(Roof\ acceleration\ without\ control)} \right) \quad (6)$$

- (4) The average value of ratio of the maximum displacement responses of control mass block:  $J_6$

$$J_6 = average \left( \frac{\max(|Mass\ displacement\ with\ SAMD|)}{\max(|Mass\ displacement\ with\ TMD|)} \right) \quad (7)$$

All indices of control performance are the Smaller the Better, STB.

The analysis flowchart of this paper is shown in Fig. 4. The first step of analysis process is set up structural parameter of shear building, the next step is set up the basic control parameters of TMD and SAMD, the third step is set up the frequency ratio range of control block  $\gamma_f$ ,  $0.8145 \sim 1.9480$  for TMD Controlled and  $1.0 \sim 6.0$  for SAMD controlled respectively. The fourth step is set twenty-six seismic records, listed in table 1 as input seismic forces. Then, the nonlinear dynamic analysis program with One-Dimensional Vector Form Instinct Finite Element Method, VFIFE is applied to analyze the structural responses and to find the statistical values of the maximum displacement responses of the top floor, the RMS of the top floor displacement, the maximum acceleration responses of the top floor, and the maximum displacement responses of the mass block. Finally, calculate the average value of ratio of the maximum roof displacement responses,  $J_1$ , the average value of ratio of RMS of roof displacement responses,  $J_3$ , the average value of ratio of the absolute maximum roof acceleration responses:  $J_5$  and the average value of ratio of the maximum displacement responses of control mass block,  $J_6$  to compare the control performance of shear building under control of TMD and SAMD respectively.

## 5. Analysis results and discussions

### 5.1 Shock absorption effect of roof displacement

The shock absorption effects of roof displacement of building under TMD and SAMD control under excitation of Kobe 1995 and Sumatra 2007 earthquake records are compared to discuss about the roof displacement responses

**Table 1.** Analysis setting value.

Analysis parameter category		Parameter range			
Parameters of main structure		Structure type: 10 DOF shear building Storey mass: $m_a = 200$ tn Inter-storey stiffness: $k_a = 883,645$ kN/m Inter-storey dampinfg: $c_a = 2813$ kN s/m 1 <sup>st</sup> modal frequency: $f_0 = 1.0$ Hz 1 <sup>st</sup> modal damping ratio: $\zeta_0 = 0.01$ Material Property: Reinforced Concrete Foundation: Mat Foundation			
	Earthquake	Year	Epi. Dist. (km)	Dir.	PG A(g)
Seismic waves	Kobe	1995	1	NS	8.21
	Northbridge(1)	1994	4	EW	17.45
	Barbara	1978	14	NS	3.40
	Chi-Chi	1999	18	NS	2.57
	Northbridge(2)	1994	19	EW	5.72
	Northbridge(3)	1994	23	EW	8.66
	Norcialtaly(1)	2016	28	-	2.06
	Northbridge(4)	1994	38	EW	3.48
	Northbridge(5)	1994	40	-	1.64
	Norcialtaly(2)	2016	40	-	2.55
	Loma Prieta	1989	48	NS	3.62
Calexico	2010	109	EW	4.91	
Chile	2010	109	EW	5.94	
Sumatra	2007	125	EW	1.24	
Chile(1)	2016	136	-	2.24	
Chile(2)	2010	168	-	2.68	
Chile(3)	2010	170	EW	2.32	
Chile(4)	2010	170	EW	4.66	
Chile(5)	2010	175	EW	2.34	
Chile(6)	1980	209	NS	6.84	
Chile(7)	1980	230	NS	3.37	
Alaska	2016	254	EW	2.07	
Chile(8)	1980	274	NS	3.19	
Chile(9)	2010	333	NS	4.61	
Chile(10)	2010	334	NS	2.39	
Chile(11)	2010	339	NS	3.02	

reduction ratio and RMS roof displacement responses reduction ratio.

Figures 5 and 6 show the time history of roof displacement responses of structure without control and under control of TMD and SAMD, subjected to Kobe 1995 earthquake as Near-Fault and Sumatra 2007 earthquake as Far-Field earthquake records. Figure 5 displays that there is not enough time for mass damper accumulated kinetic energy before the first wave of the main shock arrived. Thus, control effect is very small at the maximum displacement. But, root mean square of displacement responses should have good shock absorption effects. On the contrary, for the Far-Field earthquakes, delay of earthquake motion is long. Mass damper (TMD and SAMD) have considerable kinetic energy prior to the arrival of main shock. Impact of main shock wave can be controlled effectively, shown in figure 6.

Shock absorption of roof displacement responses is 9.9% and 15.8% for structure with TMD and SAMD under excitation of Kobe 1995 earthquake respectively. Otherwise, roof displacement responses reduction ratio is 52.7% and 62.1% for structure with TMD and SAMD under excitation of Sumatra 2007 earthquake respectively. Shock absorption effect of roof displacement for structure with SAMD is about 6~10% better than that of structure with TMD. Seismic proof effects of structure with TMD and SAMD are affected by types of seismic wave. Root mean square roof displacement responses reduction ratio for structure with TMD and SAMD are 67.9% and 70.9% for structure under excitation of near-fault earthquakes respectively. Otherwise, those are 55.7% and 66.3% for structure under excitation of Sumatra 2007 earthquake respectively. Shock absorption effects of these two dampers are satisfactory.

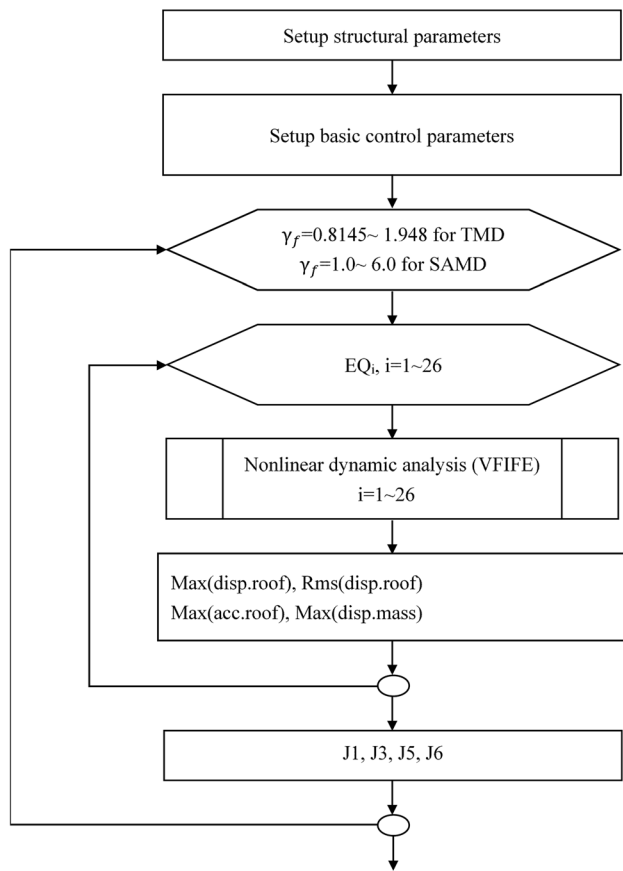


Figure 4. Flowchart of numerical simulation

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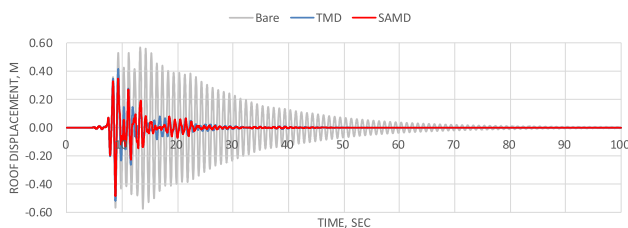


Figure 5. Roof displacement response under Kobe 1995 earthquake.

5.2 Control performance valuation

The average response ratio of maximum roof displacement, average response ratio of root means square roof displacement, average response ratio of maximum roof acceleration and average response of maximum mass displacement of shear building under excitation of 26 seismic records are compared to discuss the control effect of TMD and SAMD control under excitation of near fault earthquakes and far-field earthquakes.

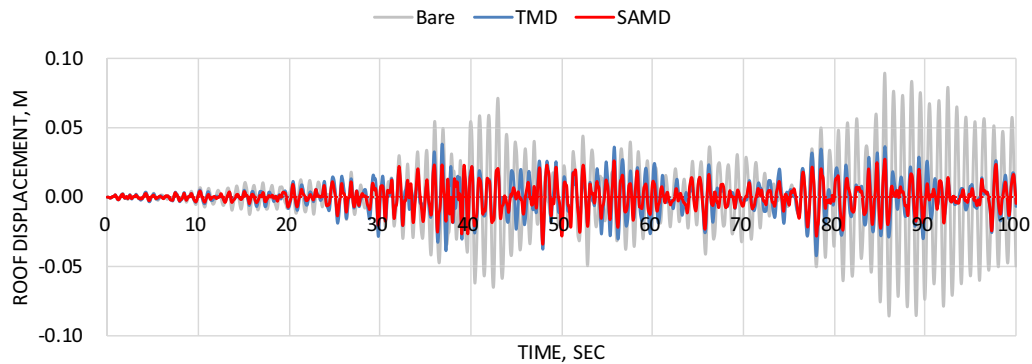
5.2a Discussion of the maximum roof displacement responses: Figure 7(a) shows that  $J_1$  increases from 0.92 to 0.98 for shear building with TMD controlled and  $\gamma_f = 0.8 \sim 1.2$  under excitation of near-fault earthquakes, then  $\gamma_f > 1.2$ ,  $J_1$  approaches to 1.0. When shear building under excitation of far-filed earthquakes with  $\gamma_f = 0.8 \sim 1.2$ ,  $J_1$  drops from 0.78 to 0.68, then increases to 0.83. The average ratio of the maximum roof displacement responses of shear building under excitation of 26 seismic records  $J_1$  drops from 0.80 to 0.72, then increases to 0.82. But,  $J_1$  increases gradually to 0.9 with  $\gamma_f > 1.4$ . Figure 7(a) shows that the TMD control effect for building is heavily influenced by the frequency ratio, the control effect is only at narrow frequency wide. Therefore, TMD is less suitable for structural displacement control of building under excitation of near fault earthquakes.

Figure 8(a) displays that  $J_1$  lies between 0.82 and 0.87 for shear building with SAMD controlled and  $\gamma_f = 1.0 \sim 6.0$  under excitation of near-fault earthquakes. When shear building under excitation of far-filed earthquakes,  $J_1$  drops from 0.75 to 0.62 and then increases gradually to 0.68 till  $\gamma_f = 6.0$ . The average ratio of the maximum roof displacement responses of shear building under excitation of 26 seismic records  $J_1$  drops from 0.75 to 0.65, then increases to 0.69 till  $\gamma_f = 6.0$ . Figure 8(a) shows that the maximum displacement of the top floor under SAMD control is very flat for the change curve of the frequency ratio. That is, the control effect is very insensitive to the frequency ratio. Although the control effect of building under SAMD control is better than that under TMD control on near fault earthquakes, it is clear that SAMD is also more applicable to far-field earthquakes.

The comparison of figures 7(a) and 8(a) show that the control effect of building under SAMD control is better than that under TMD control. SAMD is almost without “de-tuning effect”.

5.2b Discssion of root mean square of roof displacement responses,  $J_3$ : Figure 7(b) shows that  $J_3$  drops from 0.58 to 0.47, then increases to 0.71 for shear building with TMD controlled  $\gamma_f = 0.8 \sim 1.2$  under excitation of near-fault earthquakes, then  $\gamma_f > 1.2$ ,  $J_3$  increases gradually to 0.9. When shear building under excitation of far-filed earthquakes and 26 seismic records with  $\gamma_f = 0.8 \sim 1.2$ ,  $J_3$  drops from 0.61 to 0.47, then increases to 0.76 respectively. Then,  $J_3$  increases gradually to 1.05 for  $\gamma_f = 1.2 \sim 2.0$ . Figure 7(b) shows the same trend as  $J_1$ , and the control effect of the root mean square roof displacement is also affected by the frequency ratio. But, the conclusion of this figure is opposite to  $J_1$  on the influence of seismic waves. TMD control effects on near fault earthquakes are superior to those of far-field earthquakes.

Figure 8(b) displays that  $J_3$  drops from 0.45 to 0.36 for shear building with SAMD controlled and  $\gamma_f = 1.0 \sim 3.0$  under excitation of near-fault earthquakes, and then increases to 0.41 till  $\gamma_f = 6.0$ . When shear building under



**Figure 6.** Roof displacement response under Sumatra 2007 earthquake.

excitation of far-field earthquakes and 26 seismic records,  $J_3$  drops from 0.50 to 0.38 for  $\gamma_f = 1.0 \sim 2.2$  and then increases gradually to 0.40 at  $\gamma_f = 3.0$  and then increases gradually to 0.45 till  $\gamma_f = 6.0$ . Figure 8(b) shows that the trend of average response ratios of root mean square roof displacement are the same as these of  $J_1$ , SAMD control effect has a weak correlation to the frequency ratio. The comparison of figures 7(b) and 8(b) display that SAMD control effects on near fault earthquakes are slightly better than those of far-field earthquakes and reduce the average response ratio of root mean square roof displacement by approximately 10%, compared to the optimal control effects of TMD.

**5.2c Discussion of the absolute maximum roof acceleration responses,  $J_5$**  Figure 7(c) shows that  $J_5$  drops from 0.98 to 0.90, then increases to 0.95 for shear building with TMD controlled and  $\gamma_f = 0.8 \sim 1.2$  under excitation of near-fault earthquakes, then  $\gamma_f > 1.2$ ,  $J_5$  increases gradually to 0.98. When shear building under excitation of far-filed earthquakes and 26 seismic records with  $\gamma_f = 1.0 \sim 1.2$ ,  $J_5$  drops from 0.95 to 0.88, then increases to 0.95. Then,  $J_5$  increases gradually to 0.98 for  $\gamma_f = 1.2 \sim 2.0$ . Therefore, TMD control effect is affected by acceleration, and its sensitivity to frequency ratios and seismic waves is much lower than those of  $J_1$  and  $J_3$ .

Figure 8(c) displays that  $J_5$  is for shear building with SAMD controlled and  $\gamma_f = 1.0 \sim 2.0$  under excitation of 26 seismic records,  $J_5$  is about 0.90. The frequency ratio of building with SAMD controlled under far-field earthquakes increases slightly to 0.92 when  $\gamma_f < 3.0$ , but fluctuated significantly more than 1.0, under near fault earthquakes. When  $\gamma_f > 3.0$ , no matter what seismic waves are, average response ratios of max. roof acceleration are significantly magnified to 1.64 till  $\gamma_f = 6.0$ . The amplification phenomenon of the average response ratios of max. roof acceleration SAMD controlled are significantly enlarged when  $\gamma_f > 4.0$ . Thus, in order to take into account the max. acceleration responses of building under SAMD control, the frequency ratio of SAMD controlled should be limited to less than 4.0.

The comparison of figures 7(c) and 8(c) reveal that the average response ratios of max. roof acceleration of SAMD controlled is still better than those of TMD controlled when  $\gamma_f < 3.0$ . Therefore, while SAMD is a pulsed semi-active mass damper, as long as  $\gamma_f < 3.0$ , the acceleration amplification effect will not be caused.

**5.2d Discussion of the maximum displacement responses of control mass block,  $J_6$ :** Figure 8(d) shows that displacements of mass block for structure with SAMD is about 2 to 4 time those of TMD. These results display that large space is required to install this SAMD.

**5.2e Comprehensive discussion** Indices of optimal control performance for structure with TMD are  $J_1 = 0.92$ ,  $J_3 = 0.47$ ,  $J_5 = 0.90$  and  $J_1 = 0.68$ ,  $J_3 = 0.47$  and  $J_5 = 0.88$  for near fault and far-filed earthquakes respectively. Indices of optimal control performance for structure with SAMD are  $J_1 = 0.82$ ,  $J_3 = 0.41$ ,  $J_5 = 0.90$ ,  $J_6 = 2.50$  and  $J_1 = 0.62$ ,  $J_3 = 0.38$ ,  $J_5 = 0.9$ ,  $J_6 = 4.0$  for near fault and far-filed earthquakes respectively.  $J_1$  shows that shock absorption effect for structure with SAMD is slightly better than that of TMD. The maximum roof displacement responses can be reduced about 6~10%.  $J_3$  displays that RMS roof displacement responses can be reduced 6~9%. These values reveal that the advantages of SAMD is not obvious.  $J_5$  reveals that structural acceleration responses of structure with TMD and SAMD are almost the same.

Then, the comparisons of structure without control and with TMD, shown in figure 7 reveals that the optimal control performance indices are happened around frequency ratio = 0.95. When frequency ratio is slightly offset, control performance indices  $J_1$ ,  $J_3$  and  $J_5$  increase. Shock absorption effects are very limited, “de-tuning effect” is verified by these analysis results.

Figure 8 displays that the lowest values of  $J_1$  and  $J_3$  occur at a very gentle curve. It means that indices of control performance are very low sensitivity to frequency ratio. Shock absorption ratio of the roof displacement responses for structure with SAMD under excitation of far-field earthquake is above 38%. Seismic proof efficiency of RMS displacement responses is above 62% for structure with



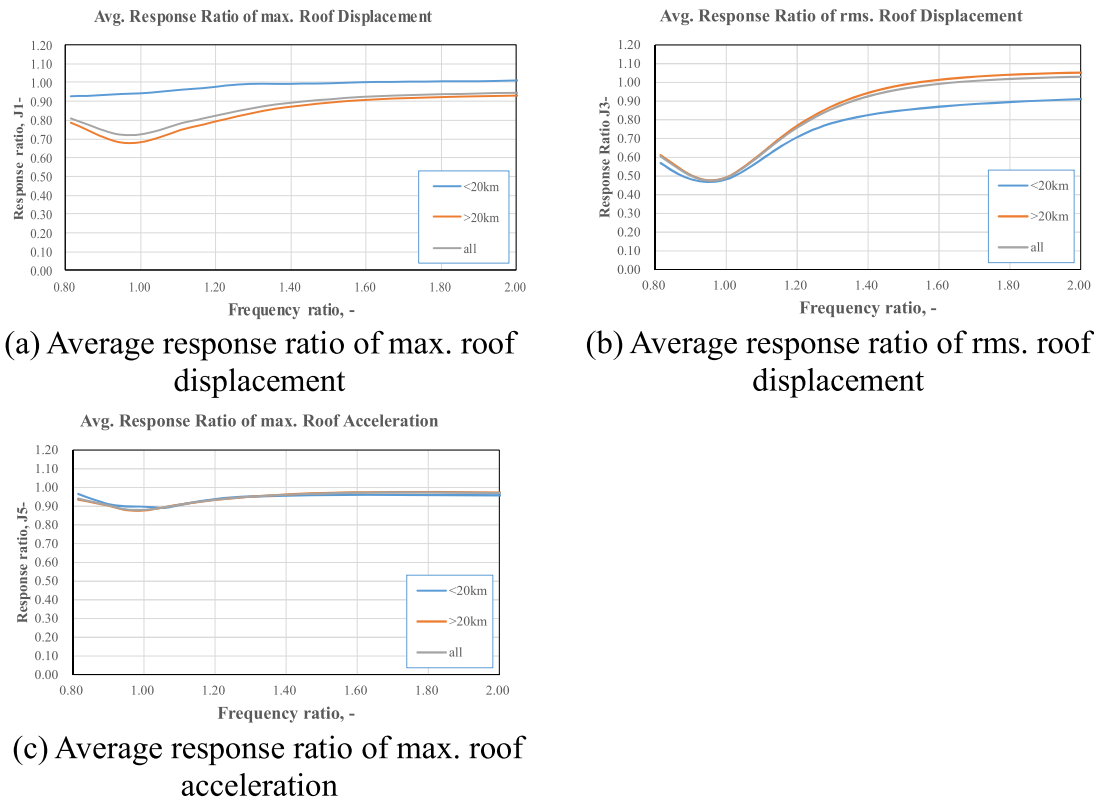


Figure 7. Response ratio of Structure with TMD.

SAMD under excitation of far-field earthquake. However, the displacement of mass block requires large installation space for SAMD.

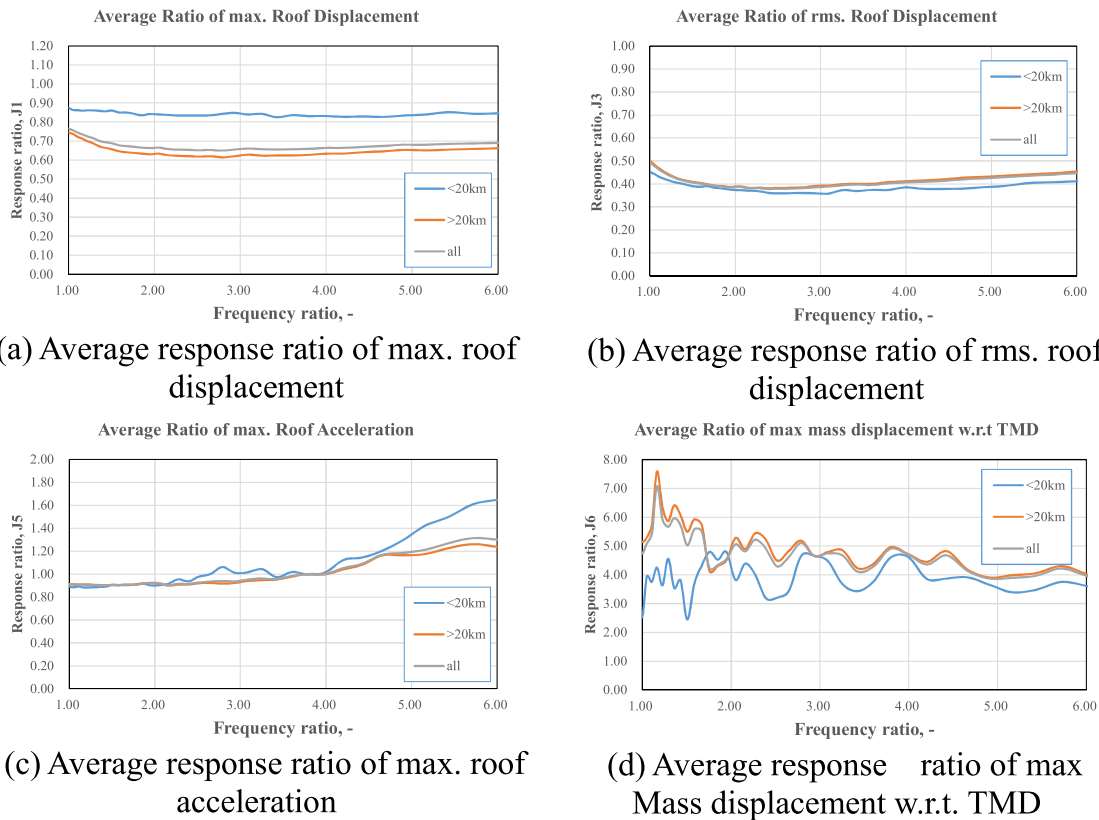
### 6. Conclusions

Analysis results of structure with TMD and SAMD with various frequency ratio and damping ratio are compared to ensure the practicability of this proposed SAMD. Otherwise, twenty-six near-fault and far-field earthquake records are applied to compare the shock absorption of the maximum roof displacement responses, root mean square roof displacement and the maximum roof acceleration for structure with TMD and SAMD. Relevant analysis results can be concluded as follows:

(1) Shock absorption of roof displacement responses and root mean square displacement responses is 9.9%, 15.8% and 67.9%, 70.9% for structure with TMD and SAMD under excitation of Kobe 1995 earthquake respectively. Shock absorption of roof displacement responses and root mean square displacement responses 52.7%, 62.1% and 55.7%, 66.3% for structure with TMD and SAMD under excitation of Sumatra 2007 earthquake respectively.

- (2) TMD control effect for building is heavily influenced by the frequency ratio, it is less suitable for structural displacement control of building under excitation of near fault earthquakes. SAMD control effect is very insensitive to the frequency ratio, it is better than that under TMD control on near fault earthquakes and also more applicable to far-field earthquakes. Otherwise, SAMD is almost without “de-tuning effect”.
- (3) Shock absorption ratio of the roof displacement responses for structure with SAMD under excitation of far-field earthquake is above 38%. Seismic proof efficiency of RMS displacement responses is above 62% for structure with SAMD under excitation of far-field earthquake.
- (4) SAMD is a pulsed semi-active mass damper, as long as  $\gamma_f < 3.0$ , the acceleration amplification effect will not be caused, the frequency ratio of SAMD controlled should be limited to less than 4.0 to avoid enlarging the max. acceleration responses.
- (5) Displacements of mass block for structure with SAMD is about 2 to 4 time those of TMD. These results display that large space is required to install this SAMD.

Synthesize the above results reveal that this proposed SAMD can avoid the “de-tuning effect” and shock absorption effect of structure with SAMD is better than that



**Figure 8.** Response ratio of Structure with SAMD with  $W_V:W_A = \omega_0 : 1$ , w/o additional damper and spring.

of TMD under excitation of 26 seismic waves records. The practicability of this proposed SAMD has been verified.

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