An Innovative Idea for Controlling the Seismic Response of Structures Based on the Use of Inertia Forces

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SUMMARY:
In this study the basic idea of seismic response control is employed, in which the control forces are of inertia type created by a set of pre-compressed springs connected to set of masses installed at the building's roof level. The main idea is sudden release of the pre-compressed springs exactly at the moment at which the story drift exceeds a pre-set threshold, so that the force in each of the released springs, which tends to push away the mass connected to it, acts in the direction opposite to that of the floor relative motion, preventing it from being excessive. To evaluate the efficiency of such control technique, a computer program was developed in MATLAB environment to calculate the system's response under the effects of earthquake excitation and the forces created by the controlling sprig-mass systems. Results show that the proposed control system can decrease the seismic response up to 50%.

Keywords: Control forces of inertia type, pre-compressed springs connected to control masses at the roof level

1. INTRODUCTION

Vibration control is an effective way to improve safety and serviceability of structures, and the first ideas in this regard by the use of inertia forces or masses, as far as the available publications show, were developed in early to mid 80s and extensively expanded during the 90s. In common active or semi-active control systems to constrain the vibration of structures, the main techniques are imposing additional damping or inertia forces, or changing the frequencies of the system (Spencer and Nagarajaiah 2003). Various ideas have been discussed by researches so far, among them using Self Mass Damper (Kidokoro 2008), Tuned Mass Damper utilizing whole weight of the top floor of the building (Makino 2008), Mode Control Seismic Design With Dynamic Mass, (Furuhashi and Ishimaru 2008) are of more interest for the authors.

In this study the basic idea of a seismic response control system is employed to propose a control technique in which the control forces are of inertia type, created by a set of pre-compressed springs connected to set of masses installed at the roof level of the building. The main idea is sudden release of the pre-compressed springs exactly at the moment at which the drift value exceeds a pre-set threshold, so that the force in each of the released springs, which tends to push away the mass connected to it, acts in the direction opposite to the direction of relative motion of the roof floor, preventing it from excessive drift. Each of the released masses can be stopped again, by some mechanical stoppers, at the moment at which its corresponding spring reaches its initial no-force state. To analyze the seismic behavior of such a controlled system, a computer program in MATLAB environment has been developed to evaluate the response of the structure under simultaneous effects of the earthquake excitation and the forces created by the controlling sprig-mass systems, after releasing. By changing the dynamical and control parameters of the system and controlling masses, including mass and stiffness of the CM, as well as the amount of initial compressive deformation in its spring, and also the amount of displacement threshold (or the control displacement), and computing the response of the structure in case of each of a set of given earthquakes, the optimal stiffness and mass proportions between the CMs and the corresponding floor masses can be evaluated. Details of calculations and the obtained numerical results are presented in the following sections of the paper.

2. THE PROPOSED CONTROL TECHNIQUE

As shown in Figure 1, in the proposed technique for using the inertia forces to control the seismic behavior of the building, two Control Masses (CMs) are employed, each one connected to a pre-compressed springs.

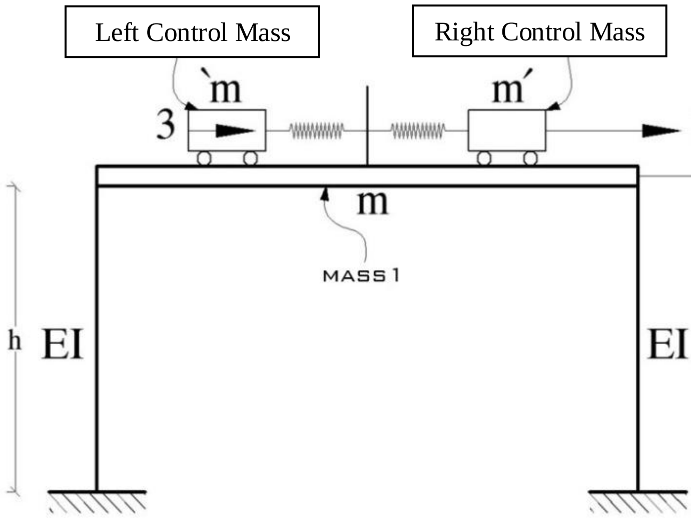

Figure 1. The proposed seismic control system with two control masses connected to pre-compressed springs

Each of the CMs is kept motionless by a specific mechanical lock. When the building is subjected to earthquake excitations, and the roof starts moving to right or left, there is an instant in which the roof displacement exceeds a defined control displacement, d_c, in either direction. At that instant one of the CMs, depending on the direction of relative motion, is released. In fact, if the roof goes to right and its displacement exceeds d_c the mass at right is released and pushed to right by the pre-compressed spring force whose reaction pushes the roof to left, trying to prevent it from excessive motion to right. On the contrary, if the roof goes to left and its displacement exceeds d_c the mass at left is released and is pushed to left by the pre-compressed spring force whose reaction pushes the roof to right, trying to prevent it from excessive motion to left. As long as the released spring is in compression the relative motion of CM and the resulting reaction force act in the desired direction, but if the spring reaches its initial length and starts acting in tension the motion of the CM and the resulting reaction force is not useful anymore. Therefore, it is better to stop each of the CMs when its corresponding spring reaches its initial length. This can be easily done by a mechanical stopper. There is also an alternative way for improving the efficiency of the control systems as explained later in the paper.

3. THE EQUATION OF MOTION FOR THE CONTROLLED BUILDING

During the earthquake, depending on the amount of roof relative motion and its direction, three different situations can be created for the controlled system. These situations are as follow.

3.1. Before Releasing of the CMs

As long as the roof relative motion is less than d_c, the whole system acts as a SDOF system, as shown in Figure 2.

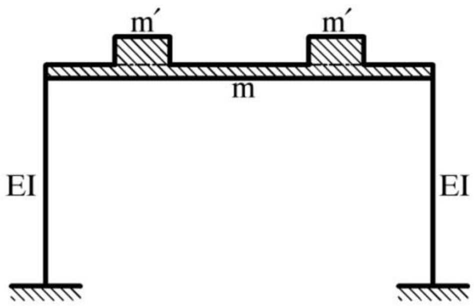

Figure 2. The whole system acting as a SDOF system before releasing of CMs

In this state the equation of motion is simply:

$$M.\ddot{u}(t) + c.u(t) + K.u(t) = -M.\ddot{u}_g(t) \tag{1}$$

where:

$$M = m + 2m' \quad \text{and} \quad K = \frac{24EI}{h^3} \tag{2}$$

The dynamic response of the system in this state can be easily obtained by any conventional methods of seismic response calculation, including New Mark method, which has been used in this study.

3.2. After Releasing of One of the CMs

As explained before, this state can be divided into two sub-states, depending on the direction of excessive relative motion of the roof. One of these sub-states in which the excessive motion of the roof to right has occurred is shown in Figure 3.

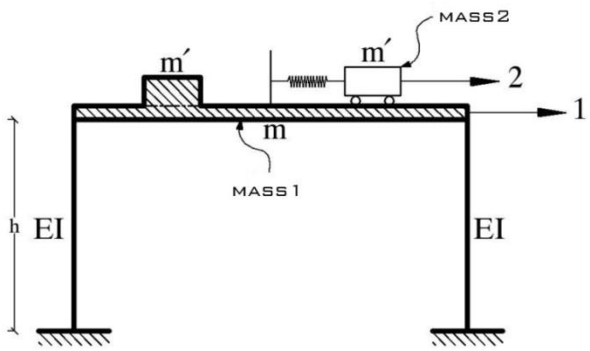

Figure 3. The state of excessive relative motion of the roof to right and releasing of the first (right) CM

In this state the system acts as a 2-DOF system whose stiffness and mass matrices are as follow:

$$[M]^{(2)} = \begin{bmatrix} m+m' & 0 \\ 0 & m' \end{bmatrix} \quad \text{and} \quad [K]^{(2)} = \begin{bmatrix} \frac{24EI}{h^3}+k' & -k' \\ -k' & k' \end{bmatrix} \tag{3}$$

in which the *m'* and *k'* are related to the CM and its spring, and superscript (2) refers to the second state of the control system. In this state the system of equations of motion is:

$$[M]\{\ddot{U}(t-t_{r1})\} + [C]\{\dot{U}(t-t_{r1})\} + [K]\{U(t-t_{r1})\} = -[M]\{r\}\ddot{u}_g(t-t_{r1}) \tag{4}$$

In Eq. (4) the damping matrix $[C]$ is assumed to be of the proportional type, t_{r1} is the instant at which the first CM is released, and vector $\{r\}$ is the earthquake influence vector for the horizontal component of ground motion, assumed here as the only effective component on the system, and is simply:

$$\{r\} = \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \tag{5}$$

It should be noted that the initial conditions for solving the system of Eq. (4) are the conditions corresponding to the last instant of the previous state, t_{r1}, at which the first CM is released, and are:

$$\left\{U_0^{(2)}\right\} = \begin{Bmatrix} u(t_{r1}) \\ u(t_{r1}) - d_0 \end{Bmatrix} = \begin{Bmatrix} d_c \\ d_c - d_0 \end{Bmatrix} \tag{6}$$

$$\left\{\dot{U}_0^{(2)}\right\} = \begin{Bmatrix} \dot{u}(t_{r1}) \\ \dot{u}(t_{r1}) \end{Bmatrix} \tag{7}$$

where d_0 is the amount of initial compressive deformation in pre-compressed springs. Again the response values including relative displacements, $u_1^{(2)}(t - t_{r1})$ and $u_2^{(2)}(t - t_{r1})$ and their corresponding velocities are obtained by a conventional dynamic response calculation technique like New Mark method.

3.3. After Releasing of the Second CM

In this state the roof has moved to the opposite direction of the second state and has exceeded the control displacement, and the second CM has been released as well. Therefore, in this state the system acts as a 3-DOF system, as shown in Figure 4.

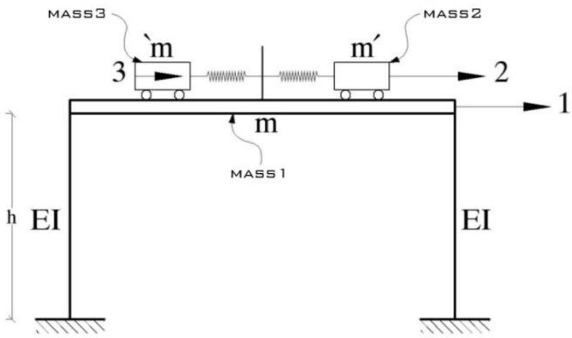

Figure 4. The state of excessive relative motion of the roof to left and releasing of the second CM

In this state the mass and stiffness matrices of the system are:

$$[M]^{(3)} = \begin{bmatrix} m & 0 & 0 \\ 0 & m' & 0 \\ 0 & 0 & m' \end{bmatrix} \tag{8}$$

$$[K]^{(3)} = \begin{bmatrix} \frac{24EI}{h^3} + 2k' & -k' & -k' \\ -k' & k' & 0 \\ -k' & 0 & k' \end{bmatrix} \tag{9}$$

in which the superscript (3) refers to the third state of the control system. In this state the system of equations of motion is:

$$[M]\{\ddot{U}(t-t_{r2})\} + [C]\{\dot{U}(t-t_{r2})\} + [K]\{U(t-t_{r2})\} = -[M]\{r\}\ddot{u}_g(t-t_{r2}) \tag{10}$$

The damping matrix $[C]$ is assumed again to be of the proportional type, t_{r2} in system of Eq. (10) is the instant at which the second CM is released, and the earthquake influence vector in this state is:

$$\{r\} = \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} \tag{10}$$

It should be noted again that the initial conditions for solving the system of Eq. (9) are the conditions corresponding to the last instant of the previous state, t_{r2}, at which the second CM is released, and are:

$$\left\{U_0^{(3)}\right\} = \begin{Bmatrix} u_1^{(2)}(t_{r2}-t_{r1}) \\ u_2^{(2)}(t_{r2}-t_{r1}) \\ u_1^{(2)}(t_{r2}-t_{r1}) + d_0 \end{Bmatrix} = \begin{Bmatrix} -d_c \\ u_2^{(2)}(t_{r2}-t_{r1}) \\ -d_c + d_0 \end{Bmatrix} \tag{11}$$

$$\left\{\dot{U}_0^{(3)}\right\} = \begin{Bmatrix} \dot{u}_1^{(2)}(t_{r2}-t_{r1}) \\ \dot{u}_2^{(2)}(t_{r2}-t_{r1}) \\ \dot{u}_1^{(2)}(t_{r2}-t_{r1}) \end{Bmatrix} \tag{12}$$

where d_0 is the amount of initial compressive deformation in pre-compressed springs. Again the response values including relative displacements, $u_1^{(3)}(t-t_{r2})$, $u_2^{(3)}(t-t_{r2})$ and $u_3^{(3)}(t-t_{r2})$, and their corresponding velocities are obtained by a conventional dynamic response calculation technique like New Mark method.

4. INCREASING THE EFFICIENCY OF THE CONTROL SYSTEM

As long as the released spring is in compression the relative motion of CM and the resulting reaction force act in the desired direction, but if the spring reaches its initial length and starts acting in tension the motion of the CM and the resulting reaction force is not useful anymore. Therefore, it is better to stop each of the CMs when its corresponding spring reaches its initial length. This can be easily done by a mechanical stopper. An alternative way for improving the efficiency of the control system is using two springs with different stiffness values and different initial lengths for each CM, so that the initial compressive deformation for the weaker spring, which is longer and is connected to the CM, is almost twice of that of the stronger spring, which is shorter and is not connected to the CM. In this way, the reacting force between the CM and the main system after releasing of the CM will be compressive for a longer time, and therefore, it will be more effective in reducing the undesired displacement of the main system. These two springs are denoted and k'_1 and k'_2 in the next section of the paper.

5. NUMERICAL RESULTS

As mentioned before, for evaluating the efficiency of the proposed control technique, a computer program in MATLAB environment has been developed to calculate the dynamic response of the structure under simultaneous effects of the earthquake excitation and the forces created by the controlling sprig-mass systems, after releasing. By changing the dynamical and control parameters of the system and controlling masses, including mass and stiffness of the CM, as well as the amount of initial compressive deformation in its spring, and also the amount of displacement threshold (or the control displacement), and computing the response of the structure in case of each of a set of given earthquakes, the optimal stiffness and mass proportions between the CMs and the corresponding floor masses can be evaluated. Figures 5 and 6 show two sample set of the response time histories of displacements and forces related to the controlled system, the CM, and also the main system without control, for two set of numerical values.

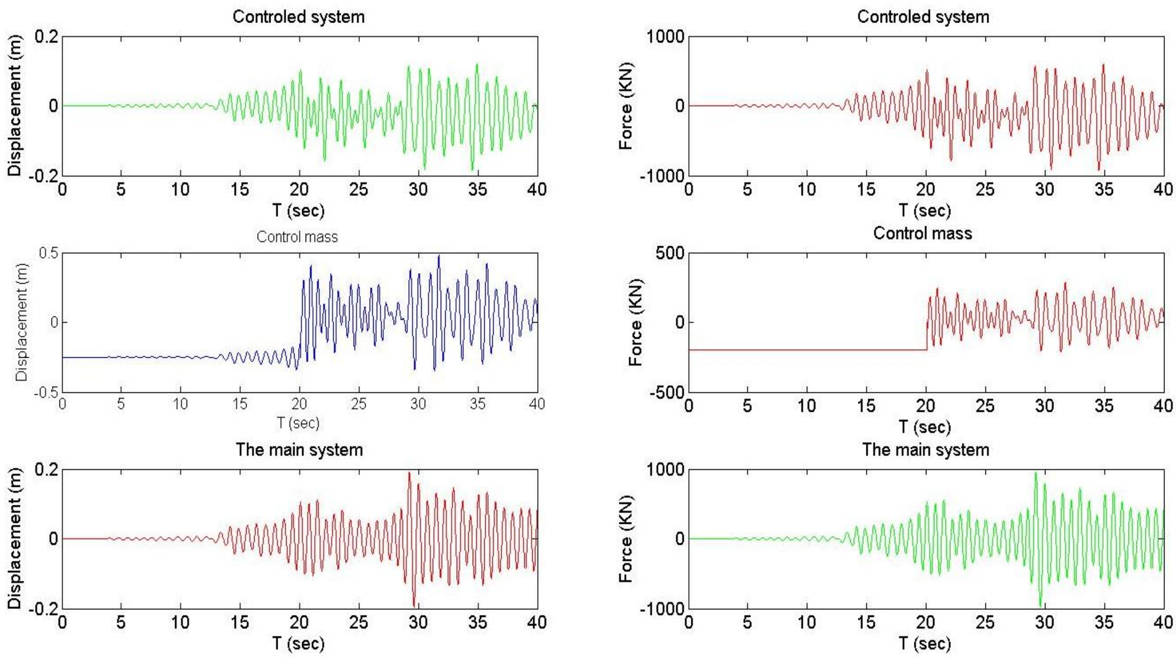

Figure 5. Sample set of the response time histories of displacements and forces related to the controlled system, the CM, and also the main system without control, for the first set of numerical values

Figure 5 corresponds to the following values for the main system and the CM as the first set of numerical examples:

$m = 50$ Ton, $m' = 7$ Ton

$k_s = 24EI/h^3 = 5000$ kN/m, k'_1 and $k'_2 = 300$ kN/m

$d_c = 0.1$ m, $d_0 = 0.4$ m, $d_{k'1} = 0.4$ m, $d_{k'2} = 0.8$ m, $d0_{k'1} = 0.15$ m, $d0_{k'2} = 0.25$ m

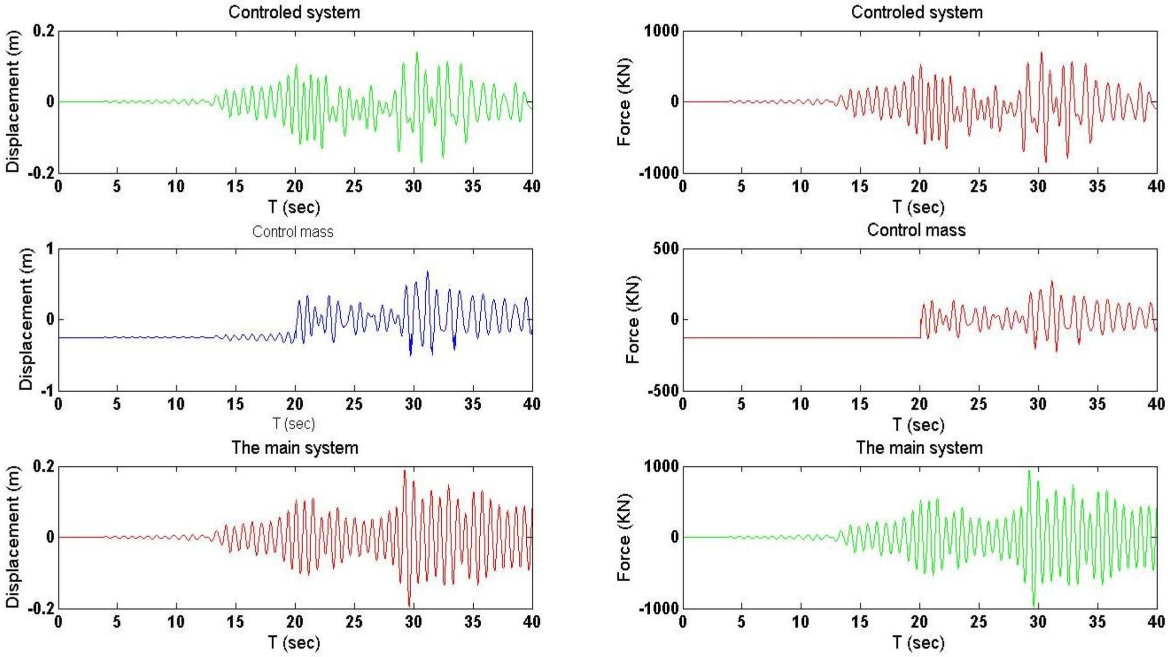

Figure 6. Sample set of the response time histories of displacements and forces related to the controlled system, the CM, and also the main system without control, for the first set of numerical values

Figure 6 corresponds to the following values for the main system and the CM as the second set of the numerical examples:

$m=50$ *Ton*, $m' = 7$ *Ton*

$k_s=24EI/h^3=5000$ *kN/m*, k'_1 and $k'_2= 200$ *kN/m*

$d_c=0.1$ *m*, $d_0=0.4$ *m*, $d_{k'1}=0.4$ *m*, $d_{k'2}=0.8$ *m*, $d0_{k'1}=0.15$ *m*, $d0_{k'2}=0.25$ *m*

It can be seen in Figures 5 and 6 that the maximum displacement response of the controlled systems has been decreased effectively due to the applied control. More results of the type shown in Figures 5 and 6 can not be given here because of the lack of space, and can be found in the main repost of the study (Karimiyan 2012). To better show the efficiency of the proposed control technique Tables 1 to 3 shows how the variation of the CM specifications affect the percent of decrease in the maximum response values of the controlled system.

Table 1. The effect of variation of the mass of the CMs on the maximum response values

m **(Ton)**	***m'*** **(Ton)**	**Displacement response (m)**			**Force response (kN)**		
		The main system	**Controlled system**	**Variation percent**	**The main system**	**Control Mass**	**Variation percent**
50	4	0.160	0.180	0.125	801	904	12.9
50	5	0.184	0.150	-0.185	920	768	-16.5
50	6	0.202	0.170	-0.158	1020	865	-15.2
50	7	0.180	0.120	-0.333	946	604	-36.2
50	8	0.160	0.150	-0.063	821	762	-7.2
50	9	0.166	0.120	-0.277	831	614	-26.1
50	10	0.180	0.200	0.111	921	1018	10.5

It is seen in Table 1 that the maximum response reduction is obtained by using a m' value of 7 Tons, which is around 14% of the mass of the original system.

Table 2. The effect of variation of first spring stiffness of the CMs on the maximum response values

k **(kN/m)**	***k'*** **(kN/m)**		**Displacement (m)**			**Force (kN)**		
	k'₁	***k'₂***	**The main system**	**Controlled system**	**Variation percent**	**The main system**	**Control Mass**	**Variation percent**
5000	100	300	0.189	0.138	-0.270	946	694	-26.6
5000	200	300	0.189	0.129	-0.317	946	647	-31.6
5000	300	300	0.189	0.120	-0.365	946	604	-36.2
5000	400	300	0.189	0.113	-0.402	946	567	-40.1
5000	500	300	0.189	0.101	-0.466	946	513	-45.8

Table 2 shows that the maximum response reduction is obtained by using a k'_1 value of 500 kN/m, which is around 10% of the stiffness of the original system, while the k'_2 value is 300 kN/m.

Table 3. The effect of variation of the second spring stiffness of the CMs on the maximum response values

k **(kN/m)**	***k'*** **(kN/m)**		**Displacement (m)**			**Force (KN)**		
	k'₁	***k'₂***	**The main system**	**Controlled system**	**Variation percent**	**The main system**	**Control Mass**	**Variation percent**
5000	300	100	0.189	0.130	-0.312	946	694	-26.6
5000	300	200	0.189	0.141	-0.254	946	706	-25.4
5000	300	300	0.189	0.120	-0.365	946	604	-36.2
5000	300	400	0.189	0.135	-0.286	946	676	-28.5
5000	300	500	0.189	0.144	-0.238	946	722	-23.7

It can be seen in Table 3 that the maximum response reduction is obtained by using a k'_2 value of 500 kN, which is around 10% of the stiffness of the original system, while the k'_1 value is 300 kN/m.

6. CONCLUSIONS

Based on the numerical results it can be said that the proposed control system can decrease the seismic response up to 40%, provided that optimal values are used for the stiffness and mass of the CMs. These values are little values, generally less than 15% of those of the original system, which makes their use quite practical. Regarding the simplicity and relatively lower costs of the proposed control system in comparison with other existing systems, the use of this system can be recommended in new buildings and even existing buildings as a retrofit technique.

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