# Research on the Dynamic Characteristics and Damping Performances of RID-Passive Mega-Sub Controlled System

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## *Abstract*

The RID-passive mega-sub controlled system is proposed in this paper, in which the RID (Rotational Inertia Dampers) are attached between the substructures and megastructures based on that RID can provide larger damping force in a less physical mass. The influence of the RID parameters (equivalent mass and equivalent damping coefficient) on the dynamic characteristics of the system is analyzed by establishing the vibration differential equation of the RID-passive mega-sub controlled system. On this basis, the damping performance of this new innovative passive mega-sub controlled system is studied. Results show that the RID parameters have different effects on the natural frequency and damping ratio of the system. The RID-passive mega-sub controlled system can effectively reduce the responses of the structural system under seismic excitation compared with the mega-sub anti-seismic system. The research results obtained in this paper can provide suggestions for the damping design of mega-sub structural system.

*Keywords: mega-sub controlled system; rotation inertia damper; dynamic characteristic; damping performance*

## 1. Introduction

As urban high-rise buildings increase, a mega-sub configuration is proposed by engineers, which consists of two major structural components, a megastructure as the load bearing main structural frame and several functional sub-structures for residential or other usage. A new method for controlling the responses of mega-sub structure under severe external loads was first introduced by Feng and Mita [1]. Feng and Mita first proposed to release the connections between the megastructure and the substructures in a mega-sub system, but without installing dampers between the megastructure and the substructures. Chai and Feng[2] subsequently improved this configuration and presented a mega-sub controlled system based on a conventional mega-sub frame, and undertook a study of its dynamic response to random wind load excitations. Recently, some studies on the optimal parameters between the substructure and megastructure have been done in order to achieve the best performance by Tian[3]. Lan *et al*. proposed a multifunction mega-sub controlled structure, this structure has the function of the mass dampers and base isolation as well as damping energy dissipation[4]. A new connection form between the substructures and megastructure was put forward by Zhang *et al.* [5], in which the top substructure was connected with the megastructure by dampers. And the studies showed that this new connection form can achieve better damping effect and also can prevent collisions between the top substructures and the megastructure, however, the limited maximum damping force of conventional viscous dampers was neglected during the research.

Rotational Inertia Dampers (RID) was proposed by Hwang et al. in 2007[6]. Isoda K *et al.* [7]-[8] have studied the dynamic characteristics and damping effect performances of a single-degree-of-freedom structural system equipped with RID. Liu *et al*.[9] have applied RID to the outrigger system for seismic mitigation. The results show that RID has good damping effect under earthquake excitation. Based on this, an innovative passive mega-sub controlled system was proposed in this paper, in which the RID was applied between the megastructure and substructure (RID-passive mega-sub controlled system), and the dynamic characteristics and damping performances of this system have been studied. The research results obtained in this paper can provide reference for the design of mega-sub structures.

## 2. RID

The basic schematic diagram of RID is shown in Fig.1. From Fig.1 it can be seen that a linear motion is transformed to rotational movement due to the ball screw; meanwhile, the small linear displacement is amplified so that more energy from the system can be dissipated in the viscous material with a relatively small damping coefficient.

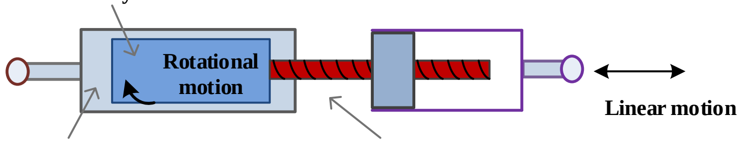



Fig. 1 – RID model

Since the RID has a moment of inertia, it will generate a rotational inertia force during operation, which can bring a "negative stiffness effect". Therefore, the final output force of the RID includes the viscous force and the "negative stiffness" force, and the force and deformation curve of RID is shown in Fig.2.

An RID can be represented as shown in Fig.3 and the force applied to it can be determined using the following expression

$$F_{RID} = b(\ddot{x} - \ddot{x}_b) + c_b(\dot{x} - \dot{x}_b)$$

where $F_{RID}$ is the equivalent force caused by RID, $b$ is the nominal mass which is equivalent amplified mass because of rotational motion, $c_b$ is the equivalent amplified damping coefficient of the RID (Hwang *et al.*, 2007), and $x$ and $x_b$ are the displacements of the upside and downside of the RID, respectively.

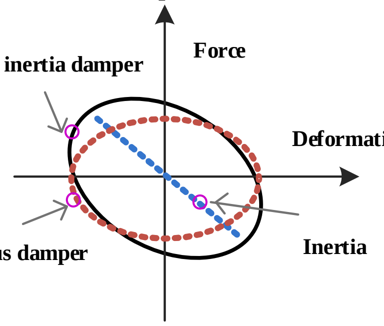



Fig. 2 – The relationship between force and deformation

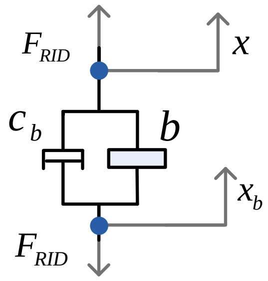



Fig. 3 – Simplified model of RID

## 3. Analytical model and equations of motion for RID-passive mega-sub controlled system

### 3.1 Analytical model for RID-passive mega-sub controlled system

For the analysis purposes, the megastructure and substructures are simplified as a series of lumped-mass model. RID are attached between the top substructure and megastructure. Fig. 4 shows the simplified analysis model for the passive mega-sub controlled system.

### 3.2 Equations of motion for RID-passive mega-sub controlled system

The equation of motion for the analysis model above can be established as follows:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{I\}\{\ddot{x}_g\} \quad (1)$$



$$[M]=\begin{bmatrix}[M_{11}] & [M_{12}]\\ [M_{21}] & [M_{22}]\end{bmatrix} \quad [M_{11}]=diag[[mq_1],...,[mq_{i-1}]] \quad [mq_n]=diag[m_1,...,m_{j-1},m_j+b_n]$$

$$[M_{12}]=[...,-b_1,...,-b_2,...,-b_{i-1},...]_{[(i-1)*j]\times i} \quad [M_{21}]=[M_{12}]^T \quad [M_{22}]=diag[M_1,M_2+b_1,...,M_i+b_{i-1}]$$

$$[K]=\begin{bmatrix}[K_{11}] & [K_{12}]\\ [K_{21}] & [K_{22}]\end{bmatrix} \quad [K_{11}]=diag[[kq_1],...,[kq_{i-1}]] \quad [kq_n]=\begin{bmatrix}k_1+k_2 & -k_2 & 0\\ -k_2 & \ddots & -k_j\\ 0 & -k_j & k_j\end{bmatrix}$$

$$[K_{12}]=[-k_1,...,-k_2,...,-k_{i-1},...]_{[(i-1)*j]\times i}$$

$$[K_{21}]=[K_{12}]^T \quad [K_{22}]=\begin{bmatrix}K_1+K_2+k_1 & -K_2 & 0\\ -K_2 & \ddots & -K_i\\ 0 & -K_i & K_i\end{bmatrix} \quad [C]=\begin{bmatrix}[C_{11}] & [C_{12}]\\ [C_{21}] & [C_{22}]\end{bmatrix} \quad [C_{11}]=diag[[cq_1],...,[cq_{i-1}]]$$

$$[cq_n]=\begin{bmatrix}c_1+c_2 & -c_2 & 0\\ -c_2 & \ddots & -c_j\\ 0 & -c_j & c_j+cb_n\end{bmatrix} \quad [C_{12}]=[-c_1,...,-cb_1,...,-c_{i-1},....-cb_{i-1},...]_{[(i-1)*j]\times i} \quad [C_{21}]=[C_{12}]^T$$

$$[C_{22}]=\begin{bmatrix}C_1+C_2+c_1 & -C_2 & 0 & 0\\ -C_2 & C_2+C_3+c_2+cb_1 & -C_3 & 0\\ 0 & -C_3 & \ddots & -C_i\\ 0 & 0 & -C_i & C_i+cb_{i-1}\end{bmatrix}$$

where $m_j$, $c_j$, $k_j$ are the equivalent mass, damping and stiffness of each substructure, respectively; while $M_i$ , $C_i$ , $K_i$ are the equivalent mass, damping and stiffness of each megastructure, respectively; $b_j$ , $c_{bj}$ are the equivalent mass and damping coefficient of RID, $\{x\}=\{\{x_j\} \quad \{x_i\}\}^{\mathrm{T}}$ ,$\{x_j\}$,$\{x_i\}$ are the displacement of the substructure and megastructure relative to the ground respectively; $\ddot{x}_g$ is the ground motion acceleration.

## 4. Dynamic characteristic analysis of RID-passive mega-sub controlled system

A typical project is selected as an example [10], which is composed of five mega-stories and the substructures are attached to megastructure from the second floor to the fifth floor. The mass and shear stiffness of each megastructure are $9\times10^5$ kg and $9\times10^7$ N/m respectively, and the mass of top megastructure is $4.5\times10^5$ kg. The mass of each substructure is determined by the mass ratio $u$, and $u$ is taken as 1. Each substructure has the same parameter values. When the megastructure is simplified as a series of particle-based model, its first period is 2s, and the fundamental period of the structure is 2.8s when the substructures are rigidly connected with the megastructures.

The state variables are defined as follows

$$\mathbf{Y}=\begin{Bmatrix}\mathbf{X}\\ \dot{\mathbf{X}}\end{Bmatrix} \tag{2}$$

Then the state equation can be obtained

$$\dot{\mathbf{Y}}=\mathbf{AY}+\mathbf{B}\ddot{x}_g(t) \tag{3}$$

where $\mathbf{A}=\begin{bmatrix}\mathbf{0} & \mathbf{I}\\ \mathbf{-M^{-1}K} & \mathbf{-M^{-1}C}\end{bmatrix}$, $\mathbf{B}=\begin{bmatrix}\mathbf{0}\\ \mathbf{-M^{-1}MI}\end{bmatrix}$



According to Eq. (3), the dynamic characteristic equation of RID-passive mega-sub controlled system is obtained.

$$\left|\lambda_0 \mathbf{I} - \mathbf{A}\right| = 0 \tag{4}$$

where $I$ is the identity matrix and $\lambda_0$ is the complex eigenvalue. $\lambda_0$ can be expressed as follows

$$\lambda_0 = -\xi\omega_0 \pm i\sqrt{1-\xi^2}\,\omega_0 \tag{5}$$

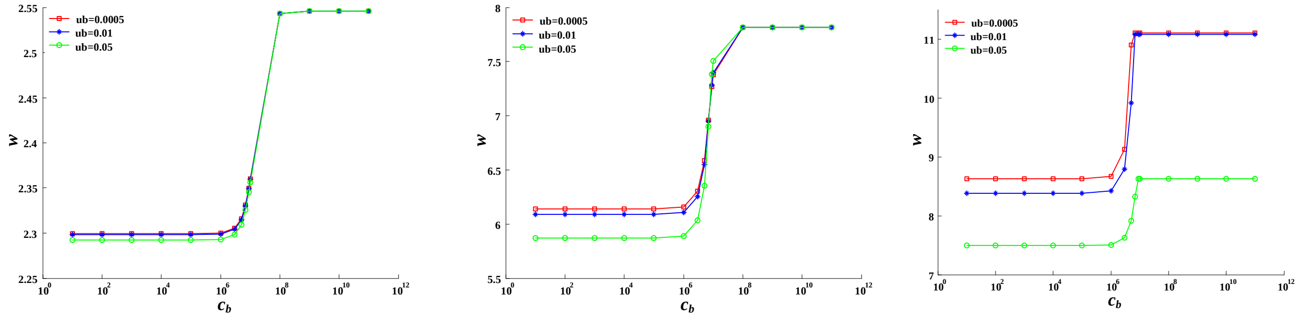
where $w_0$ is the pseudo-natural circular frequency and $\xi$ is the damping ratio for the system, which are calculated by

$$\omega_0 = \left|\lambda_0\right| \tag{6}$$

$$\xi = -\frac{\mathrm{Re}\left(\lambda_0\right)}{\left|\lambda_0\right|} \tag{7}$$

$u_b$ is the inertial mass ratio, defined as the ratio of the equivalent mass $b$ of the RID to the overall mass of the megastructure. The changes of the first three orders of natural frequency and damping ratio of the system with $u_b$ and $c_b$ are studied when the $u_b$ are taken as 0.0005, 0.01, and 0.05 respectively and the $c_b$ are taken as 0, 10, $1\times10^2$, $1\times10^3$, $1\times10^4$, $1\times10^5$, $1\times10^6$, $3\times10^6$, $5\times10^6$, $7\times10^6$, $9\times10^6$, $1\times10^7$, $1\times10^8$, $1\times10^9$, $1\times10^{10}$, $1\times10^{11}$ respectively.

Fig.4 illustrates the changes of the first three orders of natural frequency of the system with $c_b$, when the $u_b$ are taken as 0.0005, 0.01, and 0.05 respectively. It can be seen from Fig.4 that with the increase of $u_b$, the natural frequency of the system tends to decrease, especially the second and third order frequencies change significantly. When $u_b$ is constant and the damping coefficient takes a certain range of values, the frequency of the system increases with the damping coefficient. When the damping coefficient is small or large, the natural frequency of the system tends to a certain value .




(a) (b) (c)

Fig. 4 –The relationship between the natural frequency of the system and the damping coefficient under different $u_b$: (a) first-order frequency, (b) second-order frequency, (c) third-order frequency.

Fig.5 illustrates the changes of the first three orders of damping ratio of the system with $c_b$, when the $u_b$ are taken as 0.0005, 0.01, and 0.05 respectively. It can be seen from Fig.5 that with the increase of $u_b$, the damping ratio of the system increases, especially the second and third order damping ratios change significantly. When $u_b$ is constant, as the damping coefficient increases, the first and second order damping ratio of the system first increases and then decreases with the damping coefficient. The third-order damping ratio of the system increases as the damping coefficient increases and finally tend to a certain value.



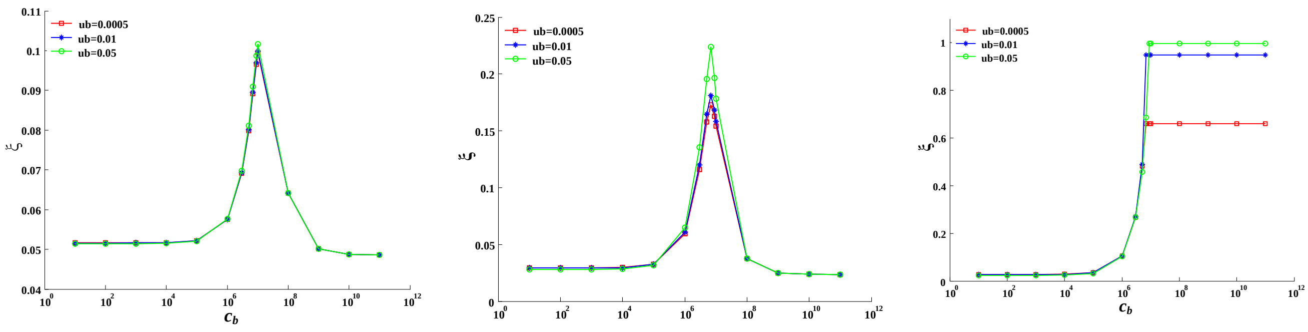



Fig. 5 –The relationship between the damping ratio of the system and the damping coefficient under different $u_b$: (a) first-order damping ratio, (b) second-order damping ratio, (c) third-order damping ratio.

From Fig.4-Fig.5, it can be seen that the equivalent mass *b* and equivalent damping coefficient $c_b$ of the RID both have some influence on the natural frequency and damping ratio of the system. When $c_b$ is constant, with the equivalent mass *b* increasing, the natural frequency of the system decreases and the damping ratio of the system increases; when *b* is constant, the natural frequency and the damping ratio of the system both have a maximum versus $c_b$.

## 5. Damping performances analysis of RID-passive mega-sub controlled system

The structural analysis model is the same as that used in section 4. The equivalent mass *b* and equivalent damping coefficient $c_b$ of the RID are taken as $2\times10^4$kg、$1\times10^7$ respectively according to the studies in section 4. Both the El Centro ground motion and Taft ground motion are employed for the seismic excitation and the PGA of them are taken as 0.3 g.

Fig.6-Fig.8 show the comparison of the megastructure layer displacement, the substructure layer displacement and the substructure layer acceleration between the mega-sub aseismic system (without RID) and the RID-mega-sub controlled system. As can be seen from Fig.6-Fig.8, the megastructure layer displacement, the substructure layer displacement and the substructure layer acceleration of the RID-mega-sub controlled system under El Centro ground motion decrease significantly compared with the aseismic system; the megastructure layer displacement, the substructure layer displacement of the RID-mega-sub controlled system decrease significantly under Taft ground motion, while the substructure layer acceleration decrease unobvious compared with the aseismic system. In general, the application of RID dampers in the mega-sub system can effectively reduce the seismic response of the structure.

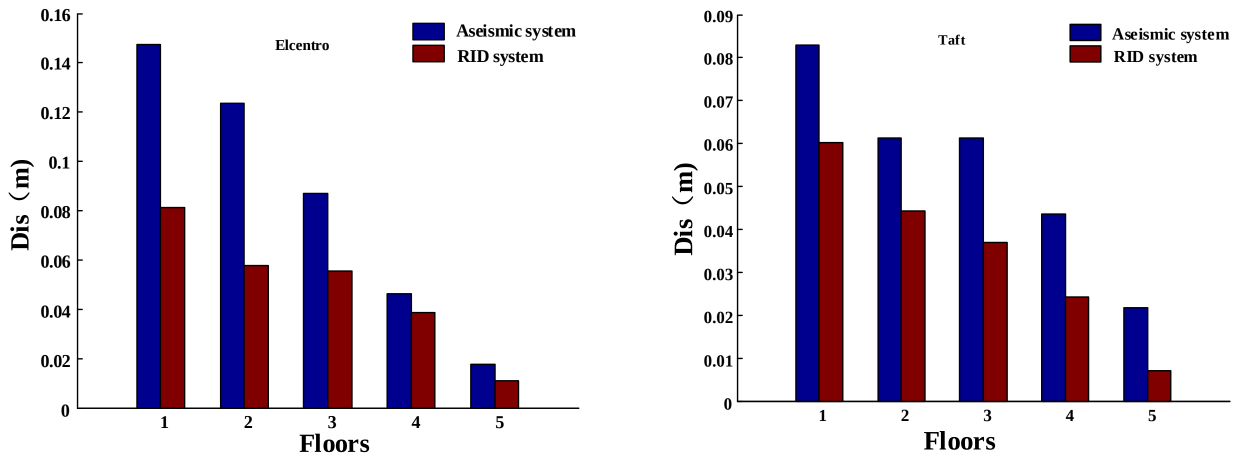



Fig. 6 – Comparison of the interlayer displacement of megastructure

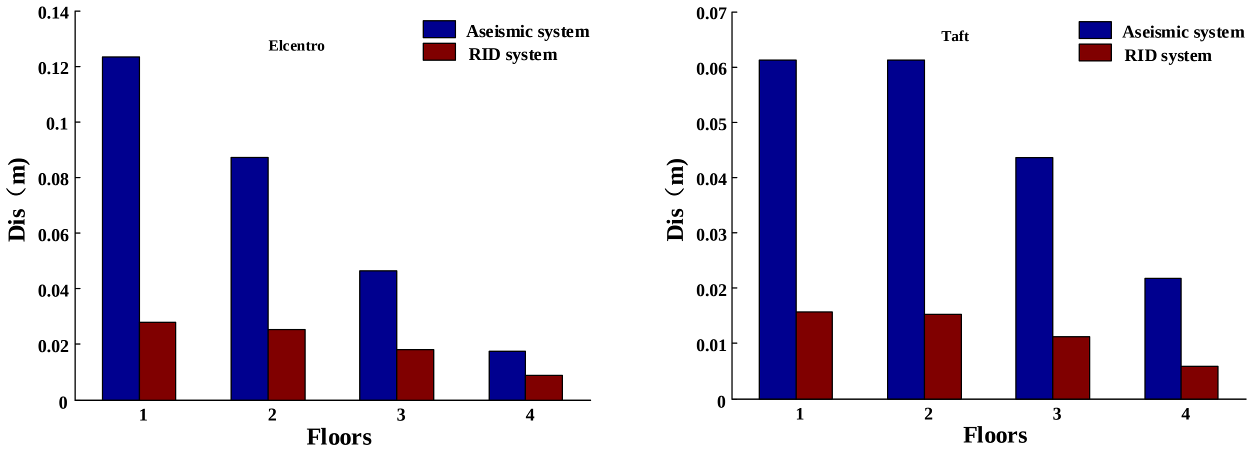



Fig. 7 –Comparison of the interlayer displacement of substructure

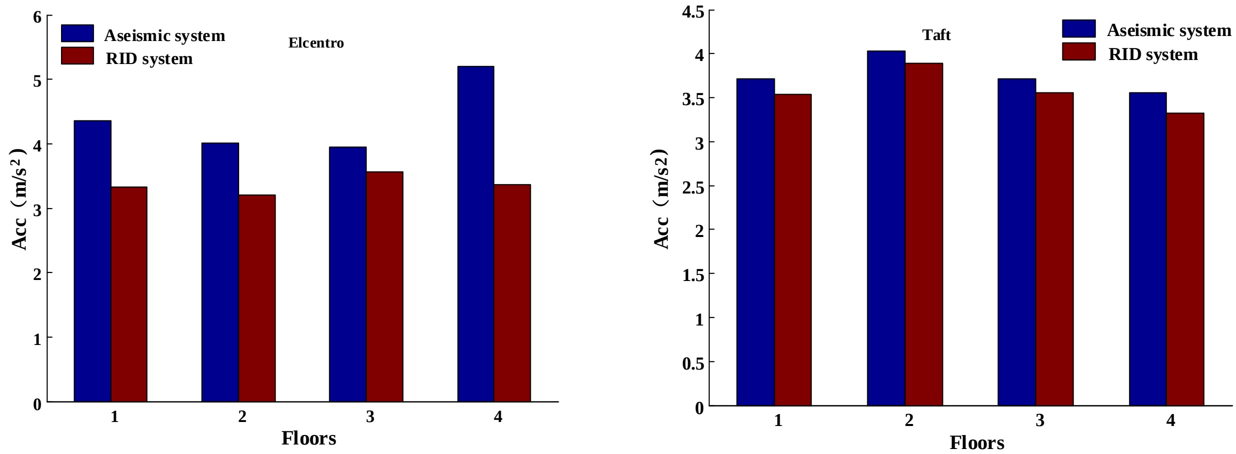
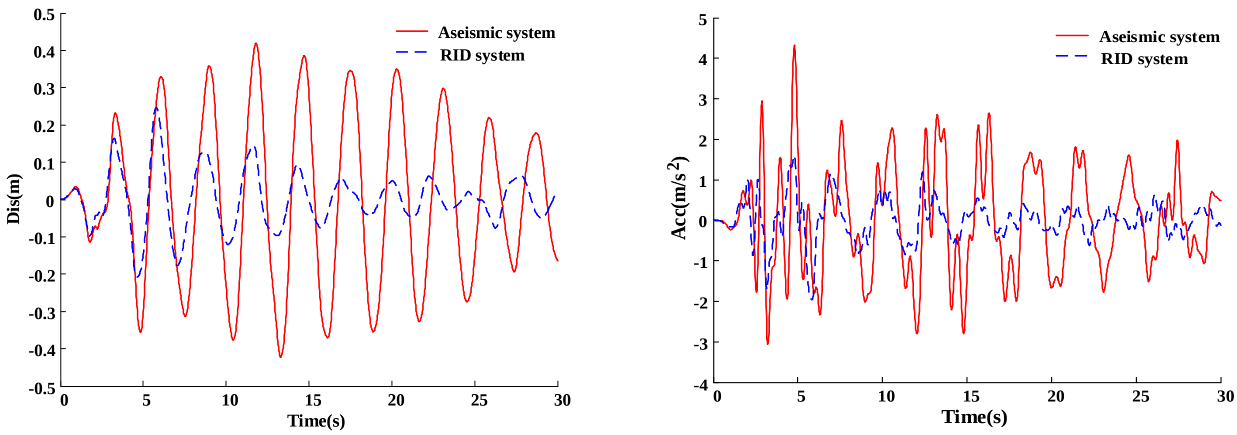



Fig. 8 – Comparison of the acceleration of substructure

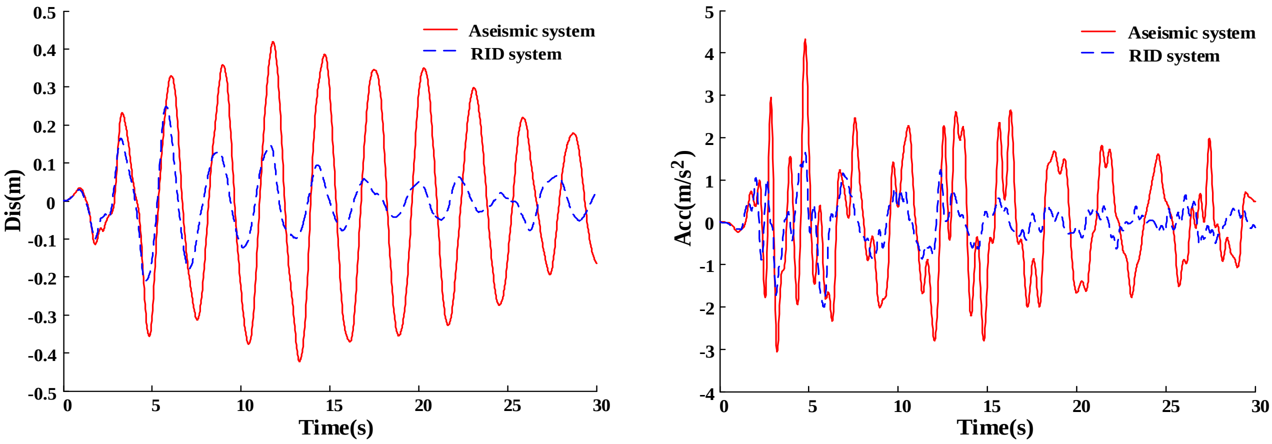
The time history responses at the top megastructure and top substructure under El Centro ground motion are shown in Fig.9. The numerical simulation results show that the RID-passive mega-sub controlled system has excellent control performance for displacement and acceleration on both the megastructure and substructure. Damping coefficient in megastructure are 0.41 in displacement and 0.55 in acceleration, and 0.40 in displacement and 0.54 in acceleration for substructure.




(a) (b)

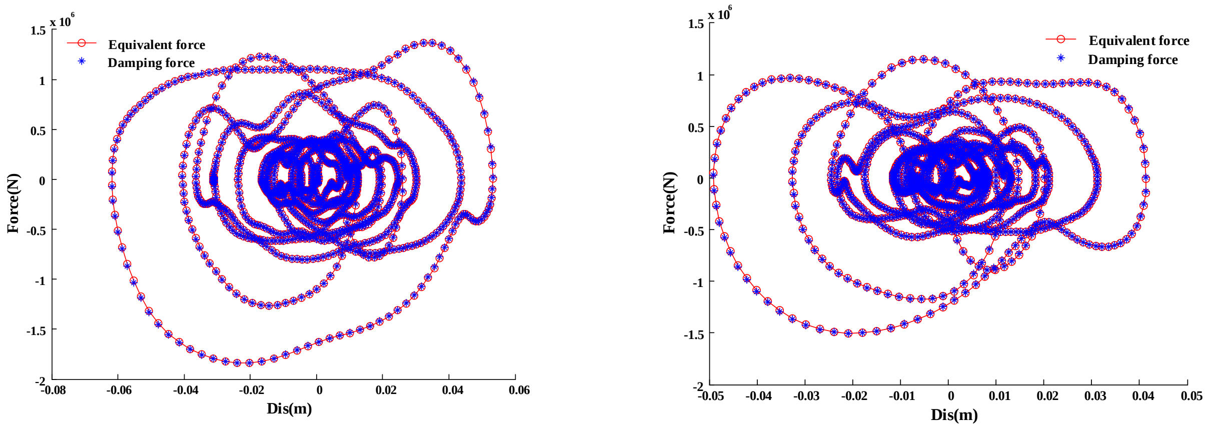


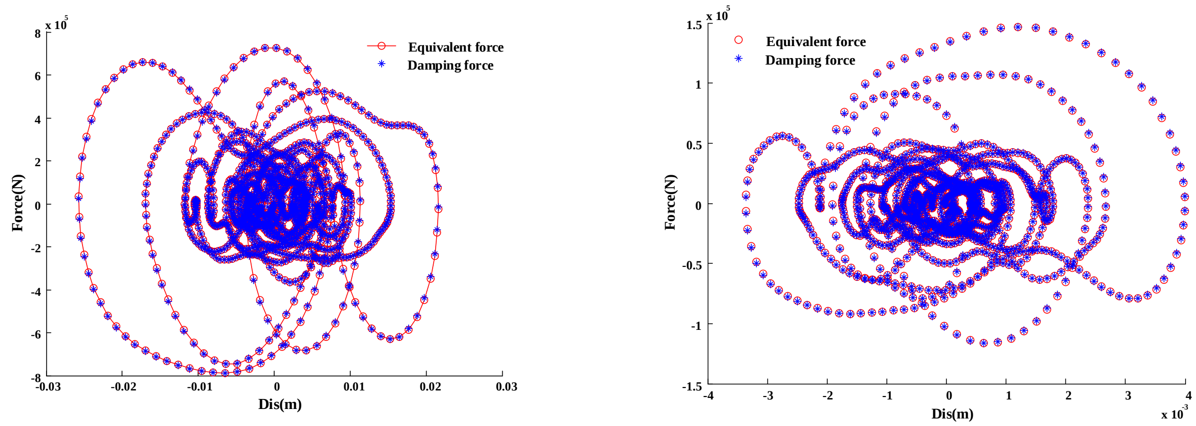



(c) (d)

Fig. 9 –Comparison of the time history responses under Elcentro ground motion: (a) the time history responses of the displacement at the top megastructure, (b) the time history responses of the acceleration at the top megastructure, (c) the time history responses of the displacement at the top substructure,(d) the time history responses of the acceleration at the top substructurel.




(a) (b)




(c) (d)

Fig. 10 –Force-deformation relationship under El Centro excitation: (a) second floor RID, (b) third floor RID, (c) fourth floor RID, (d) fifth floor RID.



Fig.10 presents the force-displacement relationship of the RID-passive mega-sub controlled system subjected to El Centro excitation. Note that the total equivalent force includes both damping force and inertial force caused by RID. From Fig.10 it can easily be found that the damping force in each layer of RID has a good consistency with the equivalent force, that is, the damping force of RID is predominant while the inertial force is negligible.

## 6. Conclusions

Based on that RID can provide larger damping force in a less physical mass, the RID-passive mega-sub controlled system is proposed in this paper. The influence of the RID parameters on the dynamic characteristics of this system has been analyzed, and the damping performance of this innovative passive mega-sub controlled system has also been studied. The following conclusions can be drawn:

(1) The equivalent mass $b$ and equivalent damping coefficient $c_b$ of the RID both have some influence on the natural frequency and damping ratio of the system. When $c_b$ is constant, with the equivalent mass $b$ increasing, the natural frequency of the system decreases and the damping ratio of the system increases; when $b$ is constant, the natural frequency and the damping ratio of the system both have a maximum versus $c_b$.

(2) The RID-passive mega-sub controlled system can effectively reduce the seismic responses of both the megastructure and substructure compared with that of the mega-sub aseismic system.

(3) The damping force in RID is predominant and the inertial force is insignificant.

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