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# Research on Active Control of Mega-sub Controlled Structure with Dampers Subjected to Seismic Loads

Xiangjun Qin, Xun'an Zhang, Ling Zou, Qianqian Wang, and Ping Jiao

*Abstract*—**Mega-sub controlled structure (MSCS) is a new form of super tall buildings associated with excellent earthquake-resistant capability. However, As the dynamic behavior and response characteristics of a practical MSCS with active control is different from the MSCS which is only installed additional dampers, it is necessary to further investigate its control mechanism and control effectiveness. In this paper, a new control method is proposed which employ active control and passive dampers together to form a huge control system based on the particular conformation characteristic of MSCS. Active control, for mega-sub controlled structure subjected to seismic loads is investigated based on LQR algorithm. Dynamic equation and method to assembling parameter matrixes for the meg-sub controlled structure under seismic ground motions are presented. Moreover, the additional damping ratio, the weight matrixes are defined and a study of the two parameters that influences the response control effectiveness, control force and dynamic characteristic of the MSCS is discussed; the regulative relationship between additional damping ratio and active control parameter is also analyzed. The result indicates that the new structure employing active control can further reduce the responses of this building. With control parameter changes, the effectiveness that influences the dynamic responses of mega-frame and substructure by additional damping value is different. Therefore, when active control is adopted on MSCS, it's necessary to adjust the damping value according to the size of the matrix to obtain the optimal control performance and active control force synthetically. This lay a foundation for further studying seismic performance and design of steel mega frame structures.**

***Index Terms*—control effectiveness, mega-sub controlled structure, seismic ground motion, active control, additional damper**

## I. INTRODUCTION

It's important to investigate new structure system which is more secure, economical, reliable and satisfy the function require along with the development of tall and super tall building [1]. Mega frame is a new structure conformation, it reflects the trend of constructing tall building for multi-functionality, good overall performance, low cost and can be assembled by a variety of structural forms and materials, this structure has been used in construction of many high buildings and super high buildings, e.g., the Bank of China at Hong Kong and Tokyo City Hall at Japan. In such kind structures, the mega-sub controlled structure (MSCS) (Figure 1) was attached importance to part scholars and has been widely investigated due to the MSCS system can provide a large amount of energy for control and is very effective in reducing structural displacement and acceleration responses [2]. The MSCS consists of two major components: a mega-frame, which is the main structural frame in the building, and several substructures, each containing many storeys that are used for commercial and/or residential purposes. In order to eliminate pounding between the mega-frame and its substructures, an improved practical MSCS was proposed by Zhang et al. [3]-[7], in which some dampers were first installed between the mega-frame and substructure to ameliorate structural response control effect, the research show that the control effectiveness with additional dampers is further improved. Recently, Qin, Zhang, Liu, and Wang presented that some active actuators could be installed between the mega-frame and the substructures to actualize active control on the MSCS for reducing the responses [8].

However, as compared with installed viscous dampers only, when active control is applied to MSCS, the response control characteristic by additional dampers and the requirements to damping of the MSCS is different, such as the distribution between additional damping and substructure, the control mechanism of structural systems, the effect on additional damping by active control parameters as well as the optimal damping value. All these are still need to be further researched.

In this paper, a steel mega-sub controlled structure is designed, whose original general configuration mega-sub frame has been employed in practical buildings, such as the Tokyo City Hall. Additional dampers and two actuators are installed between the mega-frame and the top storeys of two substructures, the optimal active control algorithm is used to analyze the system, the influence of additional damping and active control parameter on control effectiveness, control force and dynamic characteristic of the MSCS which subjected to earthquake excitation is discussed. The dynamic

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behavior and vibration characteristic of this new improved MSCS with active control is examined.

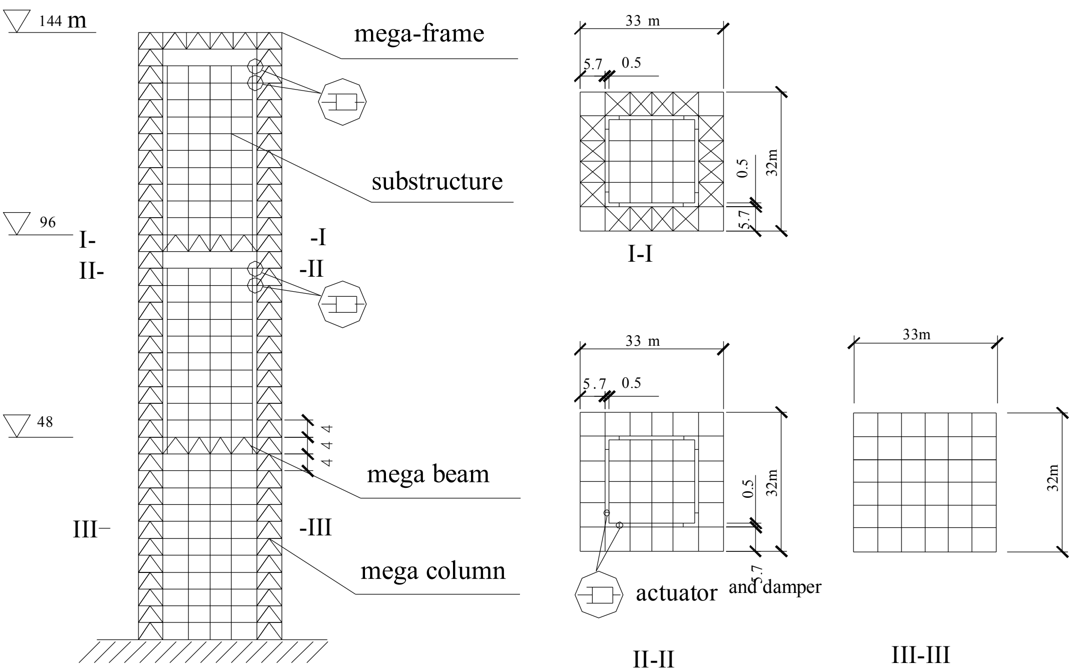


Fig.1 A steel MSCS configuration

## II. EQUATIONS OF MOTION OF THE MEGA-SUB CONTROLLED STRUCTURE SUBJECTED TO SEISMIC LOADS WITH ACTIVE CONTROL

Figure 1 shows an actual model of steel MSCS configuration, in which L1 and L2 are respectively the building's length and width, section I-I is the plan figure at the substructural top storey, section II-II is the plan at the mega-beam-storey. The gap with the amount of 450~600mm width between the mega-frame and substructure is used for installation of dampers and actuators. In this new MSCS, both the mega-frame and its substructures are modeled as MDOF systems, as shown in Fig.2. The dominant vibration mode for the mega-frame is controlled by bending deformation; shear deformation is the governing mode for the less slender substructures. A MSCS having $n$ mega-storeys and $n_s$ substructures, each of which consists of $n_z$ storeys moving relative to the mega-frame, will have a total of $N= n+ n_s \times n_z$ degrees-of-freedom. Considering active control is actualized on MSCS with dampers installed, the control equation of MSCS subjected to seismic excitations is given by:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = \boldsymbol{F}(t) + \boldsymbol{B}_s\boldsymbol{U}(t) \qquad (1)$$

where $\boldsymbol{M}$, $\boldsymbol{K}$ and $\boldsymbol{C}$ expresses the global mass matrix, stiffness matrix and damping matrix respectively [3]-[5]. $\boldsymbol{F}(t) = -G\ddot{x}_g$ ， $\boldsymbol{\Gamma}$ is the mass vector of the system, and $\ddot{x}_g$ is the seismic ground acceleration at the base of the structure. $\boldsymbol{X} = [\boldsymbol{x}_p^{\mathrm{T}}, \boldsymbol{x}_1^{\mathrm{T}}, \boldsymbol{x}_2^{\mathrm{T}}, \ldots\ldots, \boldsymbol{x}_{n_s}^{\mathrm{T}}]^{\mathrm{T}}$ is the lateral deformation vector of the system relative to its moving base with $n + n_s n_z$ variables, and $\boldsymbol{x}_p = [\boldsymbol{x}_{p,1}, \boldsymbol{x}_{p,2}, \ldots, \boldsymbol{x}_{p,n}]^{\mathrm{T}}$, $\boldsymbol{x}_i = [\boldsymbol{x}_{i,1}, \boldsymbol{x}_{i,2}, \ldots, \boldsymbol{x}_{i,n_z}]^{\mathrm{T}}$ ($i$=1,2,…, $n_s$) are the lateral deformation vectors of the mega-frame and $i^{\mathrm{th}}$ substructure, respectively. $\boldsymbol{U}(t) = [\boldsymbol{U}_1(t), \boldsymbol{U}_2(t), \ldots, \boldsymbol{U}_r(t)]^{\mathrm{T}}$ is a $r$-vector consisting of $r$ control forces; $\boldsymbol{B}_s$ is a $N$×$r$ matrix denoting the location of $r$ actuators.

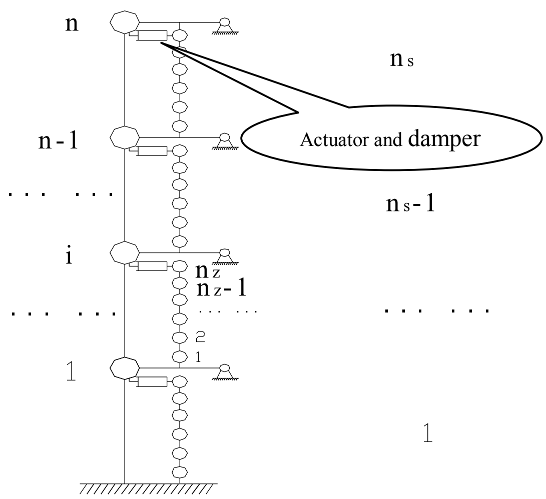


Fig.2 Computing model of MSCS

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The damping matrix $\boldsymbol{C}$ in (1) can be expressed as:

$$\boldsymbol{C}=\begin{bmatrix}\boldsymbol{C}_p+\boldsymbol{C}_{s,diag} & \boldsymbol{C}_c\\ \boldsymbol{C}_c^T & \boldsymbol{C}_s\end{bmatrix}$$

$$\boldsymbol{C}_s=diag[\boldsymbol{C}_{s,1},\boldsymbol{C}_{s,2},\mathbf{L},\boldsymbol{C}_{s,i},\mathbf{L},\boldsymbol{C}_{s,n_s}] \quad (2)$$

where $\boldsymbol{C}_p$ is the $n\times n$ damping matrix of the mega-frame, and $\boldsymbol{C}_{s,i}$ ($i$=1,2,…, $n_s$) is the $n_z\times n_z$ damping matrix of the $i^{th}$ substructure. The $n\times n_s n_z$ matrix $\boldsymbol{C}_c$ in (6) is the coupling damping matrix between the mega-frame and the substructures; its nonzero elements are expressed as:

$$\mathbf{C}_c(i,j)=\begin{cases}-c_{i+1,1} & , \ j=i\times n_z+1, \ i=1,2,\ldots\ldots,n_s-1\\ -adc-c_{i,n_z+1} & , \ j=i\times n_z, \qquad i=1,2,\ldots\ldots,n_s\\ -adc & , \ j=i\times n_z-1, \ i=1,2,3,\ldots\ldots,n_s\end{cases} \quad (3)$$

where $c_{i,1}$ is the first storey damping value of the $i^{th}$ substructure, and $adc$ is the damping value of damping devices. Finally, the matrix $\boldsymbol{C}_{s,diag}$ in equation (6) can be expressed as:

$$\mathbf{C}_{s,diag}=diag[c_{2,1}+adc+c_{1,n_Z+1},c_{3,1}+adc+c_{2,n_Z+1},\ldots\ldots,$$
$$c_{i,1}+adc+c_{i-1,n_Z+1},\ldots\ldots,c_{n_s,1}+adc+c_{n_s-1,n_Z+1},$$
$$0+adc+c_{n_s,n_Z+1}] \quad (4)$$

## III. The Active Control State Equation of Mega-Sub Controlled Structure Subjected to Seismic Loads

In the state space, equation (6) becomes

$$\dot{\boldsymbol{Z}}(t)=\boldsymbol{AZ}(t)+\boldsymbol{BU}(t)+\boldsymbol{DF}(t) \quad (5)$$

where $\boldsymbol{Z}$(t) is a $2N$ state vector; $\boldsymbol{A}$ is a $2N\times2N$ linear system matrix; $\boldsymbol{B}$ is a $2N\times r$ control location matrix; and $\boldsymbol{D}$ is a $2N\times N$ excitation influence matrix, respectively, they are:

$$\boldsymbol{Z}(t)=\begin{bmatrix}\boldsymbol{X}(t)\\ \dot{\boldsymbol{X}}(t)\end{bmatrix}, \quad \boldsymbol{A}=\begin{bmatrix}\boldsymbol{0} & \boldsymbol{I}\\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{C}\end{bmatrix},$$

$$\boldsymbol{B}=\begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{M}^{-1}\boldsymbol{B}_s\end{bmatrix}, \quad \boldsymbol{D}=\begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{M}^{-1}\end{bmatrix} \quad (6)$$

The state equation of the structure in equation (5) is the full-order system (FOS). The output feedback vector $\boldsymbol{Y}$ with $N$ measurements is expressed as:

$$\boldsymbol{Y}=\boldsymbol{GZ}(t) \quad (7)$$

where $\boldsymbol{G}$ is a $N\times2N$ observation matrix. The object of the LQR design is to determine the optimal control law $\boldsymbol{U}$, which can transfer the system from its initial state to the final state such that a given performance index is minimized [7]. For the linear time-invariant system in equation (5) without excitation, the performance index J to be minimized is given by:

$$\mathrm{J}=\frac{1}{2}\int_{t_0}^{\infty}[\boldsymbol{Z}^{\mathrm{T}}(t)\boldsymbol{QZ}(t)+\boldsymbol{U}^{\mathrm{T}}(t)\boldsymbol{RU}(t)]dt \quad (8)$$

where $\boldsymbol{Q}$ is positive semi-definite, and $\boldsymbol{R}$ is positive-definite. A minimization of the performance index J in equation (8) subject to the constraint of equation (5) results in the well-known LQR controller [9]:

$$\boldsymbol{U}(t)=-\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{PZ}(t) \quad (9)$$

In which $\boldsymbol{P}$ is the Riccati matrix satisfying the algebraic Riccati equation

$$\boldsymbol{PA}+\boldsymbol{A}^{\mathrm{T}}\boldsymbol{P}-\boldsymbol{PBR}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P}+\boldsymbol{Q}=0 \quad (10)$$

## IV. Numerical Evaluation of the Seismic Response Performance of an Example Mega-Sub Controlled Structure with Active Control

Fig.1 illustrates an example, a steel mega-sub controlled structure, and it is comprised of three mega-frames and three, 10-storey substructures. The connections between the substructures and the second and third storeys of the mega-frame have been released; this allows these flexible units to serve as relative moving, mass damped substructures, in the manner of the classical 'tuned mass damper system' [3]-[5], [10]-[11]. As indicated in the figure, dampers and two actuators are installed between the mega-frame and the top storeys of these two substructures**.** The overall building height is 144 meters, and each mega storey is 48 meters high. The structure's main members are composed of fabricated latticed mega columns and latticed mega beams, whose cross sections are 5.7m x 5.7m and 5.7m x 4.0 m, respectively. The main member sizes and properties of this building are provided in [3].In the analyses that follow, the MSCS under the *EI-Centro* (*N-S*) acceleration wave is researched; the corresponding maximal peak acceleration of this wave is 341.69531 cm/s$^2$.

The additional dampers that influence the seismic response can be expressed by this parameter: the additional damping ratio, $r_c$. It's defined as follows:

$$r_{\mathrm{c}}=\frac{adc}{C^{*}_{sub}(1)} \quad (11)$$

where $adc$ is the additional damping value of damping devices, $\mathrm{C}^{*}_{sub}(1)$ is the first storey damping value of the substructure.

To compare the dynamic performance and control effectiveness between the MSCS with active control and the MSCS without actuators, the control effectiveness, referred to as the control ratio $g$, is defined as:

$$g=\frac{Y_*-Y}{Y_*} \quad (12)$$

where $Y_*$ and $Y$ are respectively the mean value of displacement or acceleration of the MSCS with active control and without active actuators.

When LQR arithmetic is taken to design the control force, the weight matrix $\boldsymbol{Q}$ and $\boldsymbol{R}$ are two important control parameters, they determine the value magnitude of control force and structural responses. The form of $\boldsymbol{Q}$ and $\boldsymbol{R}$ are given as follows:

$$\boldsymbol{Q}=a\begin{bmatrix}\boldsymbol{K} & 0\\ 0 & \boldsymbol{M}\end{bmatrix}, \quad \boldsymbol{R}=b\boldsymbol{I} \quad (13)$$

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where $a$ and $b$ are weight parameters, $\boldsymbol{I}$ is an $2\times2$ identity matrix.

The active control force designed according to this form of $\boldsymbol{Q}$ and $\boldsymbol{R}$ will minimize the energy of system, that is, when $\boldsymbol{Q}$ and $\boldsymbol{R}$ in LQR algorithm is chosen as (13), no matter what value of $a$ and $b$ takes, the control effectiveness and the corresponding control force will be the same simultaneously as long as the ratio of $a/b$ is the same. This implies that the structural response and control force is only concerned with the ratio of $a/b$ and have nothing to do with the absolute value of $a$ and $b$ [12]. So, we assumed $a$ = 1 to investigate the relationship between the control parameters $b$ and structural responses. In this way, the control effectiveness of MSCS with active control depends on $r_c$ and $b$ .

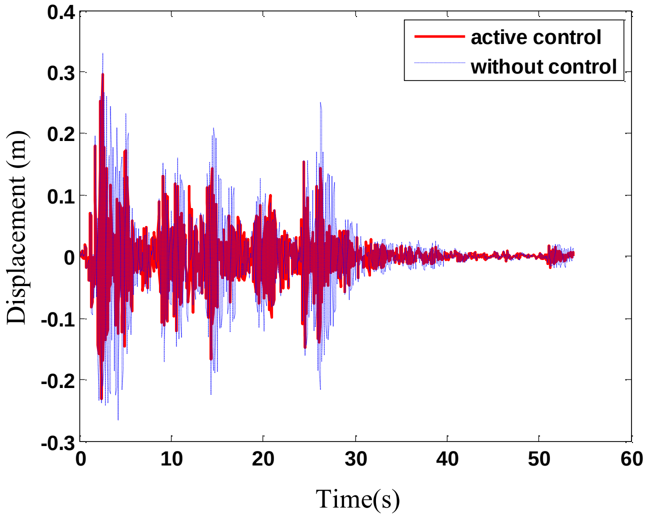


Fig.3 Time history curve of displacement at the top mega-mass of mega-frame with active control and without control, while $r_c$ =0 and $b=10^{-8}$

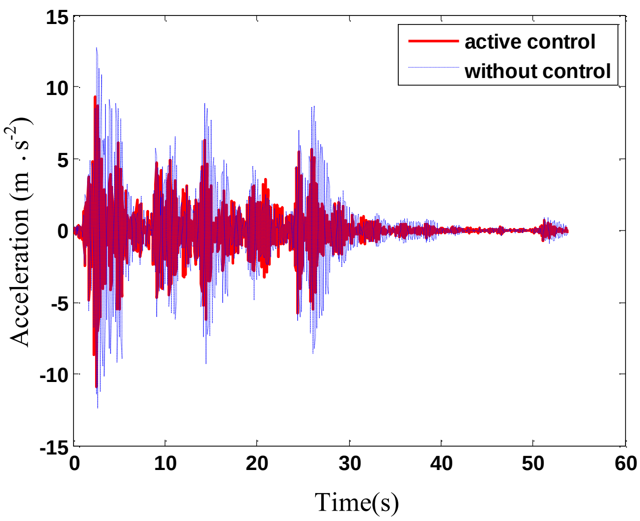


Fig.4 Time history curve of acceleration at the top sub-mass of second substructure with active control and without control, while $r_c$ =0 and $b=10^{-8}$

The seismic response time histories at the top mass of MSCS with active control and without active actuator are given in Fig.3 and Fig. 4, while $a=100$，$b=10^{-6}$ and $r_c$ =0. Note that the maximal displacement response at the top mega-mass of mega-frame without actuator is 0.3313m, and with active control is 0.2954m correspondingly, the reducing ratio is 10.84%. The maximal acceleration response at the top sub-mass of second substructure without actuator is 12.7081 m/s$^2$, and with active control is 10.9151 m/s$^2$ correspondingly, the reducing ratio is 14.11%. With active control, the displacement and acceleration responses of MSCS are all decreased evidently. It is concluded that the MSCS employing active control could effectively improve the seismic resistance capability.

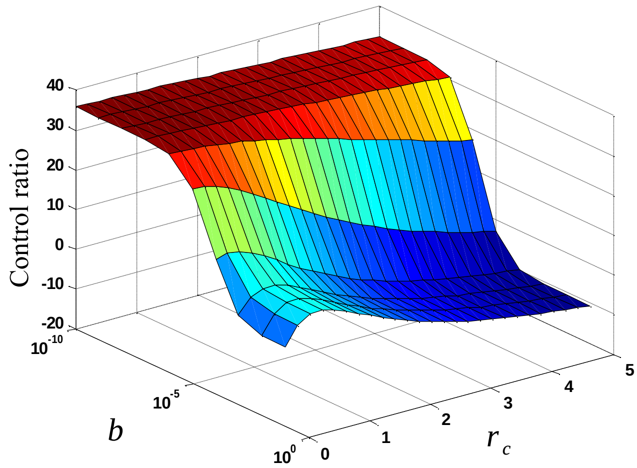


Fig.5 Control ratio of displacement responses at the top mega-mass of mega-frame while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

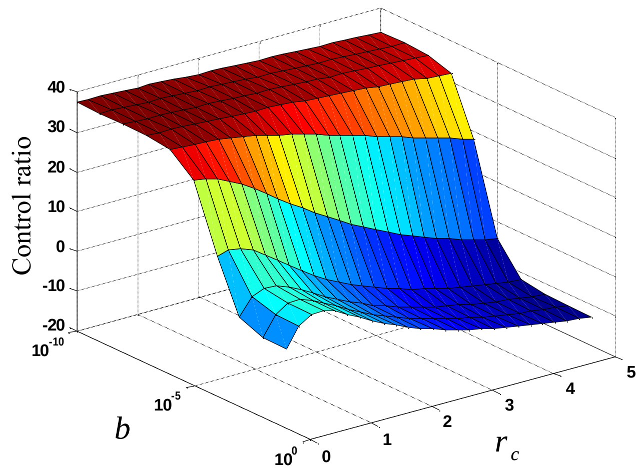


Fig.6 Control ratio of acceleration responses at the top mega-mass of mega-frame while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

Additional dampers, as a very important factor of passive control, inserted between the mega-frame and substructures, can carry out this improvement availably. For $r_c$>0, where the damping value of the added dampers are considered, as shown in Fig.5-8, the four figures summarize the results of a study of the response control ratio, for the MSCS with active control, while $a$ =1. The influences of varying the $r_c$ and

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$b$ on the displacement and acceleration response control ratio at the top mega-frame and second top substructure are illustrated respectively in these figures. Figs. 9 and 10 illustrate the variation in the maximal control force of the two actuators, respectively, as $r_c$ and $b$ are altered, while $a$ =1. From these figures the following features are seen:

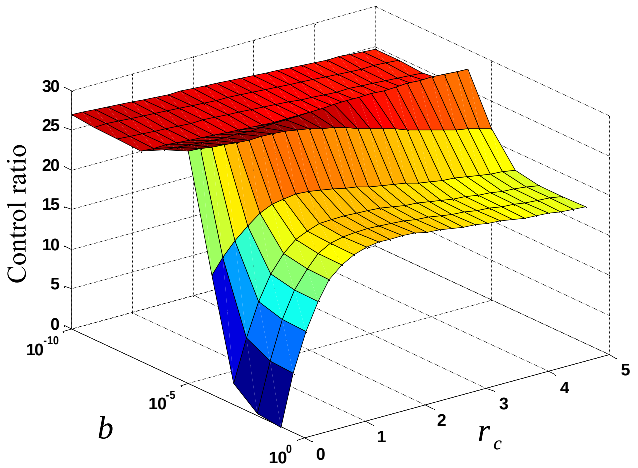


Fig.7 Control ratio of displacement responses at the top sub-mass of second substructure while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

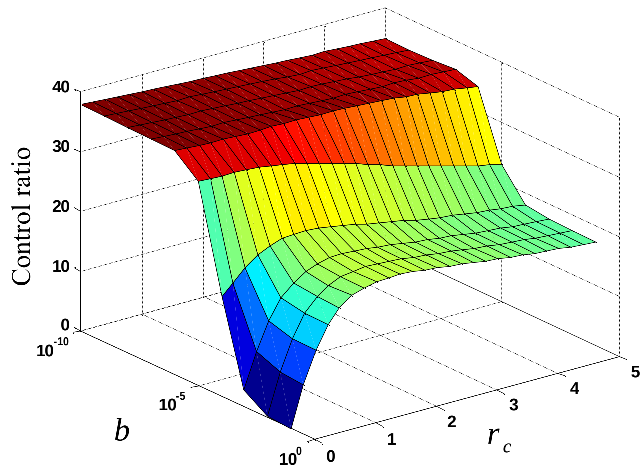


Fig.8 Control ratio of acceleration responses at the top sub-mass of second substructure while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

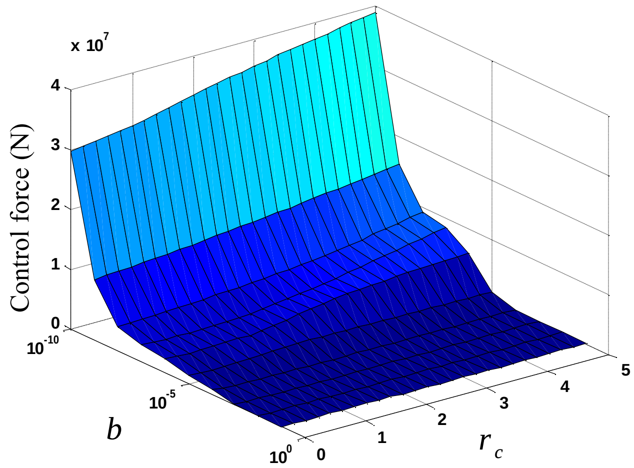


Fig.9 The maximal control force of first actuator while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

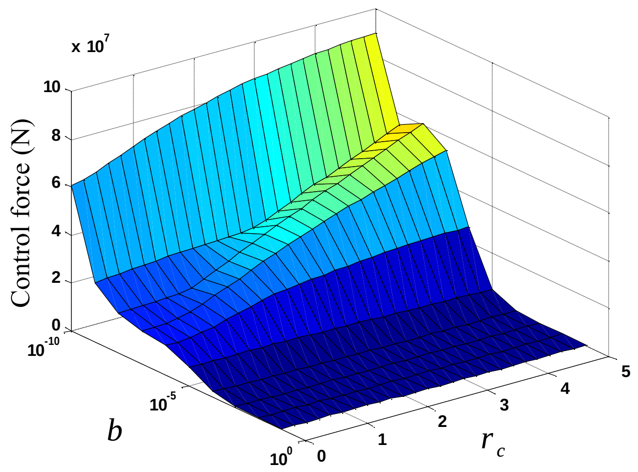


Fig.10 The maximal control force of second actuator while $r_c$ =0-5, $b$ =$10^{-10}$-$10^{-1}$

（1）No matter what values of $r_c$ is taken, when $b$ <$10^{-7}$, the structural response control ratios is high and almost do not change with $b$ decreasing, at this time via reducing $b$ can not further improve the control effectiveness. This fully shows that, a small $b$ value can make the responses control ratio of mega-frame and substructure simultaneously reaching their best effect. While $b$ >$10^{-7}$, with $b$ decreasing, the control ratio of mega-frame increases rapidly, but of substructure the control ratio increases greatly while $r_c$<1.5 and is changeless basically first then rises while $r_c$>1.5.

（2）For different $b$ , the effect played by $r_c$ on the structural response ratio is also different and closely related to $b$ . When $b$ is taken as a small value, such as $b$ <$10^{-7}$, the additional damping little impact on the structural response, this demonstrates that at this moment active control is the main control method for MSCS; when $b$ is taken as a bigger value, with the damping values increasing, the control ratio of substructure is increased greatly while $r_c$<1.5 and then remain flat, but of mega-frame would increase somewhat and subsequently decrease. The maximal control ratio of mega-frame and substructure can be obtained when $r_c$ is around 1.5.

（3）As $b$ is decreased, after a stable change, the maximal control force is increased dramatically. This demonstrates that there is a control scope for active control of MSCS, it is impossible to get control effectiveness discretionarily by increasing the control forces. With additional damping ratio increasing, the control force is also increased.

From the above we can see that, the role played by additional damping on structural responses is restricted by control parameter $b$ . The optimal control force as we commonly referred to is aimed at given weight matrixes $\boldsymbol{Q}$ and $\boldsymbol{R}$; they influence the response and control force greatly. When LQR algorithm is used, it is necessary to adjust the

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form and size of weight matrix to obtain optimal control performance and active control force together. Considering that when $b$ is small, the structural response is relatively small, at the same time the structural response will remain basically unchanged via altering the size of additional damping ratio $r_c$; furthermore, it will not affect the passive control role played by dampers when active control fails, and then the relevant additional damping value is desirable, appropriate additional damping ratio should be approximately 1.5. In view of all-sided control of system, a suitable range of two parameters can be determined: $b < 10^{-7}$, and $r_c$ is about 1.5.

## V. Conclusion

To solve the problem of pounding occurs between the mega-frame and substructures as well as further improve the structural control effectiveness of MSCS, additional dampers are installed between the mega-frame and its substructures. When active control is applied to MSCS, the control performance and characteristic is different from that of MSCS which purely installed dampers, it is necessary to further investigate its controlling mechanism and controlling effectiveness. In this paper, active control, based on optimal control algorithm for the MSCS under seismic ground motion is investigated. A practical steel mega-sub controlled structure which installed dampers with active control is investigated. The influence of additional damping ratio and active control parameter on control effectiveness, control force and dynamic characteristic of the MSCS under active control is discussed. The results demonstrate the extraordinary effectiveness of active control in controlling the displacement responses and the acceleration responses. Increasing damping value is not always means a better control effectiveness. The law of influences on the mega-frame and substructure by additional damping is not the same, and the control ratio is influenced greatly by active control parameter $b$ . A smaller $b$ will get a better control effectiveness of displacement and acceleration response. As a whole, $b$ and $r_c$ could be chosen as $b < 10^{-7}$ and $r_c$ =1.5. This result will be a useful tool for structural designers.

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