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Analysis of Dynamic Influencing Factors of Isolated Structure-Equipment Composition Systems

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Abstract: Considering the interaction between the equipment and isolated structure as well as non-proportional damping effect, the dynamic analysis model of isolated structure-equipment combination system is established. Time history analysis of the dynamic parameters about the equipment and the isolated structure, and the influence of different placed floors about the equipment on the dynamic response of the isolated structure-equipment combination system is took on. The analysis shows that the dynamic parameters of equipment and isolation structure are the main factors affecting the dynamic response of isolation structure-equipment combination system. The influence of different placed floors about equipment on the dynamic response of the composition system can be ignored, and increasing the equipment damping is the optiomal strategy to achieve the composition system damping.

At present, the use function of building structure tends to be diversified and integrated, especially in hospitals, substations, laboratories, telecommunication control centers and other important buildings with special requirements, isolation technology is used to improve the seismic performance. The number of equipment in these buildings is large and expensive. In the event of an earthquake, the building function is interrupted due to the damage of ancillary structures such as equipment, which not only causes direct or indirect huge economic losses to itself, but also brings great difficulties to post-earthquake relief and post-earthquake reconstruction. Although the isolation technology can reduce the seismic action and improve the seismic safety of the equipment, the current research methods and related design methods cannot fully guarantee the safety of the equipment and maintain the building function due to the complex dynamic interaction between the equipment and the structure, and the different dynamic response parameters and fortification requirements of the equipment and the structure. Therefore, the seismic response of the equipment needs to be more clearly defined when analyzing the isolated structure.

The research on isolation structure and equipment combination system mainly focuses on dynamic analysis and experimental verification. Eiji and Yundong et al. conducted seismic response tests on a hospital building with full-scale isolation technology [1-2]. The results show that in near-fault earthquakes, the use of isolation technology can reduce the seismic response of the main structure and equipment, and still maintain the use function of the hospital. However, in the long-term and long-term duration earthquake, the secondary structure and movable medical facilities will have a large displacement, and part of the use function of the hospital will be lost.

Kon et al. analyzed the influence of isolation system on the sliding response of equipment under earthquake. Studies have shown that isolation system can effectively inhibit the sliding of equipment in general; however, in some special cases, especially in high intensity or low friction coefficient, isolation will increase the sliding of equipment [3]. Guo et al.[4] analyzed the influence of nonlinear main structure on dynamic response of substructure by random vibration method. Han et al. simplified the isolation structure and equipment as linear. Considering the interaction between the isolation structure and the equipment, the influence of equipment quality, equipment damping ratio and isolation layer damping ratio on the floor response spectrum was analyzed [5]. Considering the nonlinearity of isolated structure, Dang et al. studied the influence of dynamic parameters of isolated structure, dynamic parameters of equipment and site conditions on floor response spectrum [6].

Therefore, aiming at the isolated structure-equipment combination system, considering the non-proportional damping effect of the isolated structure and equipment, this paper analyzes the influence of the dynamic parameters of the equipment, the dynamic parameters of the isolated structure and the location of the equipment on the seismic response of the isolated structure-equipment combination system, and draws some useful conclusions to provide reference for the seismic design of the equipment.

1. Dynamic analysis Model of Isolated Structure-Equipment Combined System Considering Dynamic Interaction

Figure 1 is a simplified calculation model of the isolated structure-equipment combination system. The isolated structure is simplified as a layer shear model, and the equipment is simplified as a linear single-degree-of-freedom system. It is located on the first floor and is fixedly connected to the floor. The mass, stiffness and damping of the equipment are m_e, k_e and c_e, respectively. m_b, k_b and c_b are the mass of the isolation layer, the stiffness of the isolation layer and the damping of the isolation layer respectively. $m_1 \sim m_n$, $k_1 \sim k_n$ and $c_1 \sim c_n$ are the mass of each layer of the main structure, the stiffness of each layer of the main structure and the damping of each layer of the main structure respectively.

Therefore, the motion equation of the isolated structure-equipment combination system can be written as,

$$M\ddot{Y} + C\dot{Y} + KY = -ME\ddot{u}_g \tag{1}$$

In the formula: $\boldsymbol{Y}$, $\dot{\boldsymbol{Y}}$, $\ddot{\boldsymbol{Y}}$ represent the displacement, velocity and acceleration of the composite system relative to the ground ; among them, $\boldsymbol{Y} = \{y_b \quad y_1 \quad \cdots \quad y_n \quad y_e\}^{\mathrm{T}}$, y_b, y_i, y_e are the isolation layer, the first layer of the main structure, and the displacement of the equipment relative to the ground. $E = [1 \quad \cdots \quad 1]^{\mathrm{T}}$ is the ground motion position matrix, $\ddot{u}_g$ is the ground horizontal acceleration.

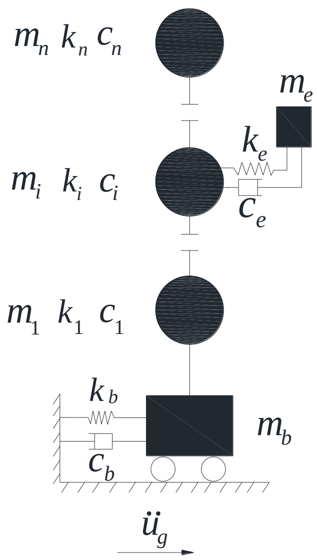


Figure 1: Calculation diagram of isolated structure-equipment composition systems

M , K are mass matrix and stiffness matrix, respectively,

$$M=\begin{bmatrix} m_b & & & & \\ & m_1 & & & \\ & & \ddots & & \\ & & & m_n & \\ & & & & m_e \end{bmatrix} \tag{2}$$

$$K=\begin{bmatrix} k_b+k_1 & -k_1 & & & & & & \\ -k_1 & k_1+k_2 & -k_2 & & & & & \\ & -k_2 & \ddots & & & & & \\ & & & k_i+k_{i+1}+k_e & -k_{i+1} & & & -k_e \\ & & & -k_{i+1} & \ddots & \text{-}k_{n-1} & & \\ & & & & \text{-}k_{n-1} & k_{n-1}+k_n & -k_n & \\ & & & & & -k_n & k_n & 0 \\ & & & -k_e & & & 0 & k_e \end{bmatrix} \tag{3}$$

C is the damping matrix of the composite system. Because the damping parameters of the isolation layer and the main structure in the isolated structure are completely different, and the damping of the equipment is also different from that of the main structure. For this special non-proportional damping model, the partition Rayleigh damping can be used to obtain the damping matrix of the isolated structure-equipment composite system.,

$$C=C_0+C_r \tag{4a}$$

Where C_0 is the Rayleigh damping matrix,

$$C_0=\alpha_s M+\beta_s K \tag{4b}$$

C_r is the residual damping matrix of non-proportional damping,

$$C_r = \begin{bmatrix} c_{br} & & & & & & & & \\ & 0 & & & & & & & \\ & & \ddots & & & & & & \\ & & & 0 & & & & & \\ & & & & \underset{\text{Line } i\text{, column } i}{c_{er1}} & & & & c_{er2} \\ & & & & & 0 & & & \\ & & & & & & \ddots & & \\ & & & & & & & 0 & \\ & & & & c_{er2} & & & & c_{er} \end{bmatrix} \tag{4c}$$

Where,

$$c_{br} = (\alpha_b - \alpha_s)\ m_b + (\beta_b - \beta_s)\ k_b \tag{4d}$$

$$c_{er} = (\alpha_e - \alpha_s) m_e + (\beta_e - \beta_s) k_e \tag{4e}$$

$$c_{er1} = \alpha_e m_e - \alpha_s m_i + (\beta_e - \beta_s)\ k_e \tag{4f}$$

$$c_{er2} = (\beta_s - \beta_e)\ k_e \tag{4g}$$

α_b, β_b, α_s, β_s, α_e, β_e are Rayleigh damping ratio coefficients of isolation layer, main structure and equipment respectively.,

$$\begin{pmatrix} \alpha_b \\ \beta_b \end{pmatrix} = \frac{2\xi_b}{\omega_n + \omega_m} \begin{pmatrix} \omega_n \omega_m \\ 1 \end{pmatrix} \tag{5a}$$

$$\begin{pmatrix} \alpha_s \\ \beta_s \end{pmatrix} = \frac{2\xi}{\omega_n + \omega_m} \begin{pmatrix} \omega_n \omega_m \\ 1 \end{pmatrix} \tag{5b}$$

$$\begin{pmatrix} \alpha_e \\ \beta_e \end{pmatrix} = \frac{2\xi_e}{\omega_n + \omega_m} \begin{pmatrix} \omega_n \omega_m \\ 1 \end{pmatrix} \tag{5c}$$

In the formula : ω_n、ω_m represent the nth and mth order modal frequencies of the composite system respectively ; ξ_b, ξ, ξ_e represent the damping ratio of isolation layer, main structure and equipment respectively.

Therefore, based on the above formula, the dynamic analysis can be carried out to obtain the response of the isolated structure-equipment combination system.

2. Engineering Example Selection

An actual isolated structure is a 6-story concrete frame structure on the ground. The seismic fortification intensity is 8 degrees (0.2g), the site category is class II, and the site characteristic period Tg = 0.40 s. The third floor is placed with a large horizontal precision machine tool. The mass of the equipment is 13000 kg, the damping ratio is 0.02, the natural vibration period is 0.236 s, and the maximum acceleration that the equipment can withstand is 200 $\mathrm{cm/s^2}$. After the main structure is simplified as a layer shear model, the mass and stiffness of each layer are shown in Table 1. The mass of the isolation layer is 63831 kg, and the isolation bearing selected for the isolation layer is 26*LRB600+12*LNR600. The mechanical properties of each isolation bearing are shown in Table 2.

Table 1: Basic parameters of isolation structure

Floor	Mass(kg)	Stiffness(10^6kN/m)
6	696888.3	0.556
5	803328.5	0.623
4	803328.5	0.623
3	811153.3	0.660
2	830906.4	0.836
1	888034.8	1.160

Table 2: Seismic performance parameters of seismic isolated bearing

Type	Total thickness of rubber layers(mm)	Equivalent horizontal stiffness(kN/mm)		Equivalent damping ratio (%)	
		γ=100%	γ=250%	γ=100%	γ=250%
LRB600	120	1.681	1.04	26.5	17.8
LNR600	120	0.909	—	5	—
LRB700	140	2.096	1.213	26.5	17.8
LNR700	140	1.060	—	5	—

3 Analysis of Dynamic Influence Factors of Isolated Structure-Equipment Combination System

For the isolated structure-equipment combination system under the action of earthquake, it is necessary to ensure the functional requirements of the isolated structure, but also to ensure that the equipment is not damaged. However, for some precision instruments and equipment, it is often acceleration-sensitive equipment. Acceleration is the main reason for its damage. Excessive acceleration will reduce the accuracy of precision equipment or even unable to continue to use ; therefore, for such a combined system, this paper takes the displacement of the isolation layer under rare earthquakes, the inter-story displacement angle of the main structure under fortification earthquakes, and the acceleration of the equipment under fortification earthquakes as the control objectives.

Define: r_e , r_d , r_θ are the control index of dynamic response of isolated structure-equipment combination system.,

$$r_e = a_e / a_{e\max} \tag{6a}$$

$$r_d = u / u_{\max} \tag{6b}$$

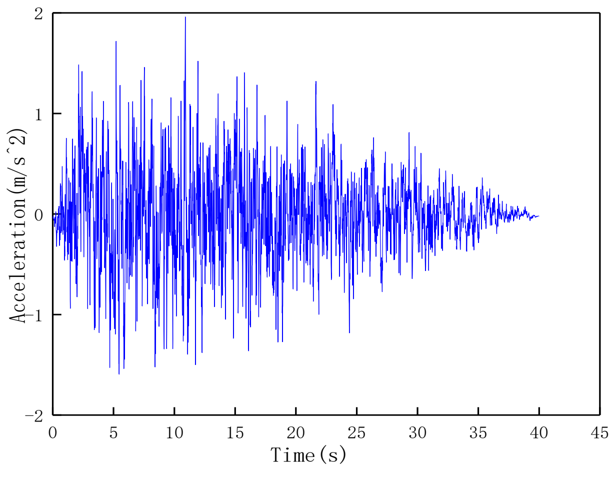
$$r_\theta = \theta_s / \theta_{\max} \tag{6c}$$

a_e is the maximum acceleration of the equipment under the fortification earthquake ; $a_{e\max}$ is the acceleration limit value of equipment under fortification earthquake, which should be determined according to the seismic parameters of equipment provided by the manufacturer. If the parameter cannot be provided, it can be obtained by analogy or test [7];

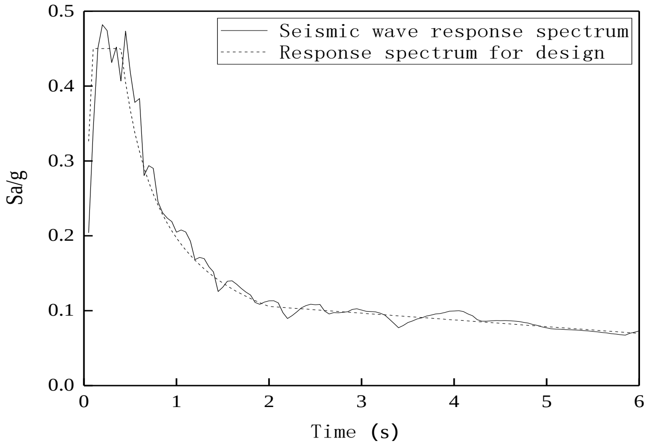
θ_s is the maximum displacement angle between the layers of the main structure under the fortification earthquake; $\theta_{\max}$ is the limit of the maximum displacement angle between layers. For the functional isolation structure with important equipment, according to the requirements of the ' Building Isolation Design Standard '[9], the main structure under the fortification earthquake is basically not damaged or can continue to use without repair. For the reinforced concrete frame structure, $\theta_{\max} = 1/400$;

u_b is the maximum horizontal displacement of isolation layer under rare earthquake ; $u_{\max}$ is the horizontal displacement limit value of the isolation layer. According to the requirements of the 'Code for Seismic Design of Buildings' [10], $u_{\max} = \min(0.55D, 3t_r)$, D is the effective diameter of the bearing, and t_r is the total rubber thickness inside the bearing.

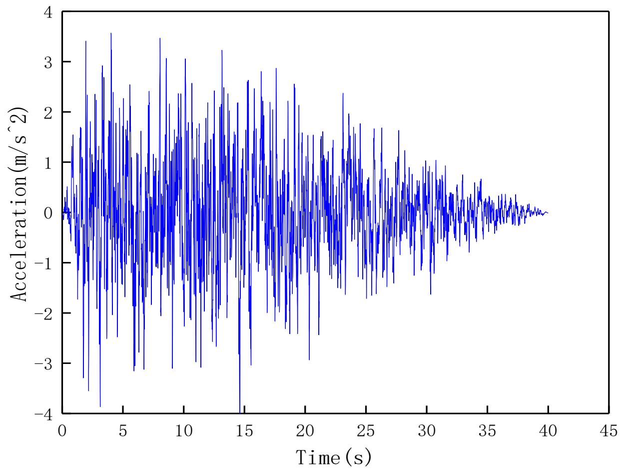
In addition, in the process of calculation and analysis, the parameters of the isolation layer and the parameters of the equipment are constantly changing, which will lead to the periodic change of the structure. In order to meet the matching of the frequency spectrum and duration of the input ground motion with the structural model, it is necessary to constantly change the input ground motion, which not only affects the calculation efficiency, but also makes the results of the time history analysis more discrete. In order to simplify the analysis and ensure that the seismic wave meets the design requirements, the ground motion is taken as the standard artificial wave, that is, when the fortification earthquake and the rare earthquake are respectively input. An artificial wave has enough duration, and the error between the corresponding response spectrum and the standard design response spectrum at each periodic point is less than 5 %. In this way, no matter how the isolation layer parameters and equipment parameters change, the standard artificial wave can meet the wave selection requirements of time history analysis. The seismic wave selected in the calculation process is shown in Figure 2.



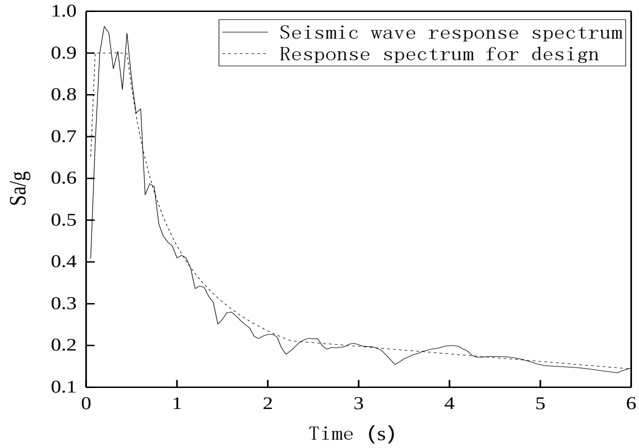
(a) Ground motion acceleration time history curve under fortification earthquake



(b) Ground motion response spectrum under fortification earthquake



(c) Ground motion acceleration time history curve under rare earthquake



(d) Ground motion response spectrum under rare earthquake

Figure 2: Standard artificial waves used during the optimization process

3.1 Equipment Mass

The mass of the equipment is 0.001, 0.01, 0.05, 0.1 of the mass of the floor. The main structural parameters, isolation layer parameters and equipment parameters are described in section 2. By changing the quality of the equipment, the control indexes of the isolation structure-equipment combination system under different equipment quality are shown in Fig.3.

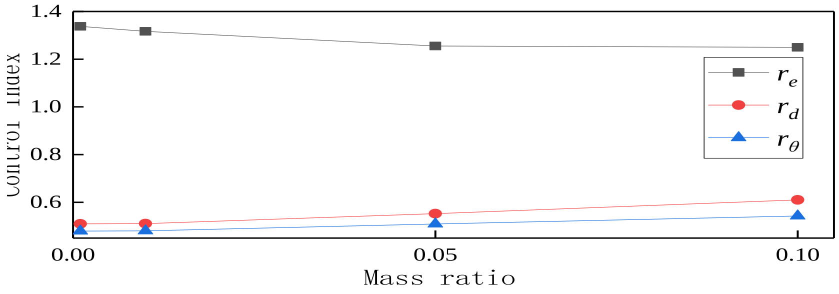


Figure 3: Control indexes of isolated structure-equipment combination system under different mass ratios

It can be seen from Fig.3 that r_e decreases and r_d and r_θ increase with the increase of mass ratio. It shows that the larger the mass of the equipment, the smaller the dynamic response of the equipment, and the more conducive to improving the seismic performance of the equipment. However, the dynamic response of the isolated structure is opposite, especially when the mass ratio of the equipment to the floor is greater than 0.01.

3.2 Equipment Damping

The damping ratios of the equipment are 0.02, 0.04, 0.06, 0.08, 0.1 respectively. The isolation structure parameters, isolation bearing arrangement and other parameters of the equipment are described in section 2. The control index of the isolated structure-equipment combination system under different equipment damping ratios is shown in figure 4.

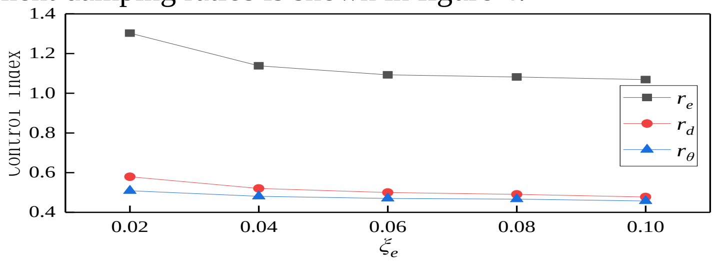


Figure 4: Control index of isolation structure-equipment combination system under different equipment damping ratio

It can be seen from figure 4 that r_e, r_d, r_θ decrease with the increase of equipment damping ratio ξ_e. It shows that increasing the equipment damping can effectively reduce the dynamic response of the isolated structure-equipment combination system, but with the increase of the equipment damping ratio ξ_e, the trend of r_e, r_d, r_θ curves tends to be gentle, indicating that the excessive increase of equipment damping is not very efficient for the damping effect of the isolated structure-equipment combination system. In general, increasing equipment damping is the preferred strategy to achieve equipment shock absorption.

3.3 Equipment Stiffness

The stiffness ratio is expressed as the ratio of the stiffness of the equipment to the stiffness of the floor where the equipment is located.

$$r_k = k_e / k_i \tag{7}$$

k_e is the stiffness of the equipment, and k_i is the stiffness of the floor where the equipment is located.

r_k is taken as 0.001, 0.01, 0.05, 0.15, 0.2 in turn. The isolation structure parameters, isolation bearing arrangement and other parameters of the equipment are described in section 2. By changing the stiffness of the equipment, the control index of the dynamic response of the isolated structure-equipment composite system under different stiffness ratios r_k is shown in Fig.5.

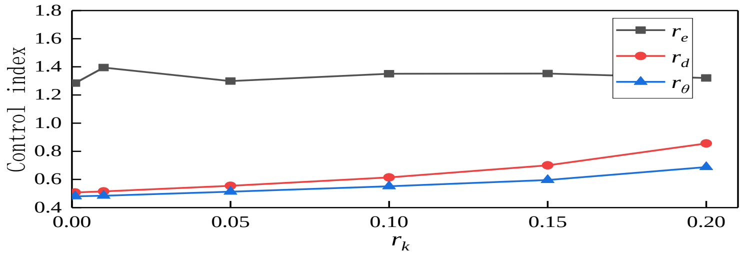


Figure 5: Control indexes of isolated structure-equipment composite system under different stiffness ratios

It can be seen from figure 5 that with the increase of stiffness ratio r_k, r_d and r_θ increase, and the change rule of r_e with r_k is not strong. It shows that the dynamic response of the equipment does not change regularly with the stiffness of the equipment, and there is an optimal equipment stiffness. The greater the stiffness of the equipment, the greater the dynamic response of the isolated structure, especially when the stiffness is more obvious than $r_k > 0.1$, indicating that the greater the stiffness of the equipment, the more unfavorable the isolated structure.

3.4 Seismic Isolation Layer Parameters

By only changing the parameters of the isolation layer, the equivalent horizontal stiffness of the isolation layer is increased by 25 % and decreased by 25 %, respectively. The corresponding isolation layer parameters are shown in table 3, and the isolation structure and equipment parameters are described in section 2. Through the time history analysis of the composite system with different isolation layer parameters, the control index of the dynamic response of the composite system is shown in Fig.6.

Table 3: Parameters of isolation layer under different bearing arrangements

Bearing arrangement		Equivalent horizontal stiffness (107N/m)	Equivalent damping ratio (%)
scheme 1	8*LRB600+30*LNR600	4.0718	12.1
scheme 2	26*LRB600+12*LNR600	5.4614	22.2
scheme 3	22*LRB600+16*LRB700	7.0518	26.5

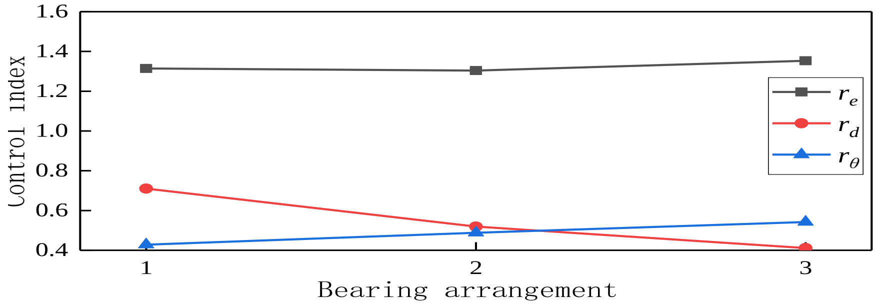


Figure 6: Control indexes of isolation structure-equipment combination system under different bearing arrangement schemes

It can be seen from Fig.6 that with the increase of isolation layer parameters, r_d decreases, r_θ increases, and r_e decreases first and then increases. It shows that the dynamic response of the equipment does not change obviously with the parameters of the isolation layer, but there is an optimal isolation layer parameter for the equipment damping. With the increase of the parameters of the isolation layer, the horizontal displacement of the isolation layer decreases and the interlayer displacement angle increases.

3.5 Floor Location of Equipment

The equipment is placed in 1 layer, 3 layers and 6 layers in turn. The isolation structure parameters, isolation bearing arrangement and equipment parameters are described in section 2. The control indexes of the isolation structure-equipment combination system under different equipment floors are shown in Fig.7.

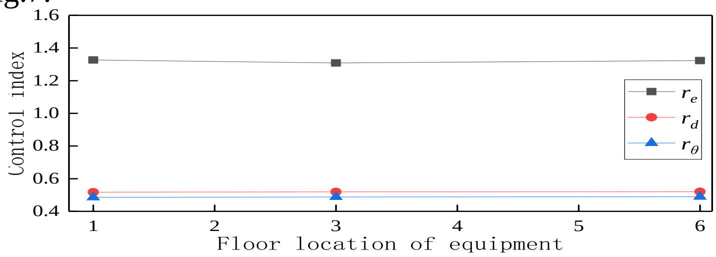


Figure 7: Control index of isolation structure-equipment combination system under different equipment floors

It can be seen from Figure 7 that with the change of the floor where the equipment is located, r_e, r_d and r_θ change slightly, but the change range does not exceed 3%. For the isolated structure-equipment combination system, the floor where the equipment is located has little effect on the dynamic response of the isolated structure-combination system and can be ignored [11-12].

4. Conclusion

In this paper, the isolation structure is simplified as an inter-story shear model, and the equipment is simplified as a linear single-degree-of-freedom system. Considering the interaction between the equipment and the isolation structure and the influence of non-proportional damping, the dynamic analysis model of the isolation structure-equipment combination system is established. The dynamic parameters of the equipment, the dynamic parameters of the isolation structure and the influence of the equipment on the dynamic response of the isolation structure-equipment combination system are analyzed. The main conclusions are as follows:

(1) The larger the mass and damping of the equipment, the better the seismic performance of the equipment, but the excessive increase of the damping of the equipment is not significant. The larger the mass and stiffness of the equipment, the more unfavorable it is to the isolation structure, especially when the mass ratio and stiffness ratio of the equipment to the floor are greater than 0.01 and 0.1 respectively. It is found that increasing the damping of equipment is the preferred strategy to realize the shock absorption of isolated structure-equipment combination system [13-14].

(2) With the increase of equivalent horizontal stiffness and equivalent damping ratio of the isolation layer, the displacement of the isolation layer decreases and the inter-story displacement angle increases. There is an optimal isolation layer parameter for equipment damping.

(3) The influence of the floor on the dynamic response of the isolated structure-equipment combination system can be ignored.

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