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Study on seismic dissipation mechanism of inter-story isolation structure based on phase

Authors:

Assoc.Prof. **Shangrong Zhang**, PhD. CE
Ningxia University, China
Faculty of Civil and Hydraulic Engineering
sr_zhang@nxu.edu.cn

Chi Zhang, MSc. CE
Ningxia University, China
Faculty of Civil and Hydraulic Engineering
zhangchi0016@163.com
Corresponding author

Xue Ju, MSc. CE
Ningxia University, China
Faculty of Civil and Hydraulic Engineering
Juxue1210@163.com

Yang Xiong, MSc. CE
Ningxia University, China
Faculty of Civil and Hydraulic Engineering
Xy18096000795@163.com

Research Paper

Shangrong Zhang, Chi Zhang, Xue Ju, Yang Xiong

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Owing to the existence of the isolation layer, a phase lag phenomenon occurs between the superstructure and substructure of a story isolation structure. This phenomenon causes a phase difference between the superstructure and substructure; furthermore, the generated phase difference has a significant impact on the structural damping effect. To study this effect, we established a two-mass model of an inter-story isolated structure, derived the phase difference formula, analysed the impact of the phase difference on the damping effect of the modelled inter-story isolated structure and obtained the optimal phase difference to achieve the best damping effect; in addition, we combined the principle of minimum base shear and optimal phase difference to optimise the damping of the structural isolation layer with different mass ratios. Based on the optimal damping, an energy balance equation was established from the viewpoint of energy. The energy transfer and consumption under different phase differences were analysed to further discuss the relationship between phase differences and the damping effect of the inter-story isolated structure.

Key words:

inter-story isolated structure, phase lag, phase difference, energy isolation mechanism

Prethodno priopćenje

Shangrong Zhang, Chi Zhang, Xue Ju, Yang Xiong

Analiza mehanizma disipacije energije međukatno izolirane konstrukcije utemeljena na zaostajanju u fazi

Kod konstrukcija koje su seizmički međukatno izolirane dolazi do fenomena vremenske odgode koji se javlja između potkonstrukcije i natkonstrukcije. Fenomen uzrokuje faznu razliku, a generirana fazna razlika ima značajan utjecaj na učinak prigušenja. Kako bi se ispitao ovaj učinak, uspostavljen je dvomaseni model konstrukcije s međukatnom izoliracijom, izvedena je formula fazne razlike, analiziran je utjecaj fazne razlike na učinak prigušenja modelirane izolirane konstrukcije te je dobivena optimalna fazna razlika za postizanje najboljega učinka prigušenja. Također smo kombinirali načelo minimalne potresne sile i optimalne fazne razlike kako bi se optimiralo prigušivanje izolacijskoga sloja konstrukcije s različitim omjerima mase. Na temelju optimalnoga prigušenja postavljena je jednadžba ravnoteže s aspekta energije. Prijenos i potrošnja energije uslijed različitih faznih razlika analizirani su kako bi se ispitao odnos između faznih razlika i učinka prigušenja izolirane međukatne konstrukcije.

Ključne riječi:

izolirana međukatna konstrukcija, vremenska odgoda, fazna razlika, mehanizam energetske izolacije

1. Introduction

The effects of earthquakes on structures are of great concern and have been extensively studied, providing many better results [1-3]. With increasing seismic requirements of building structures, isolation technology has gradually improved and is widely used in real life. The Western Post Building in Japan is an isolated building with rubber isolation bearings and it exhibited good seismic capacity during the Great Hanshin Earthquake. Not only was the building structure safe and intact, but all interior decorations, equipment and instruments were undamaged. Malatya Hospital, an isolated structure located in the eastern part of Turkey, also demonstrated good seismic performance during the magnitude 7.8 earthquake in Turkey on 6 February 2023. Beijing Daxing International Airport, located in Beijing, China, is the world's largest single isolation structure and is known as one of the "New Seven Wonders of the World". The isolation layer consists of a lead–rubber isolation bearing, an ordinary rubber isolation bearing, an elastic slide bearing and a damper. The new isolation technology was proposed based on the theory and engineering practice of base isolation structures [4]. The isolation layer of the story isolation structure is flexible and is usually set between a floor and a column, which effectively extends the scope of the isolation technology [5]. However, because of the isolation layer, the inter-story isolation structure becomes vertically irregular and its mechanical properties are very different from those of traditional structures [6, 7]. Furthermore, it also results in significantly different motion states of the superstructure and substructure.

To further understand the seismic dissipation mechanism of inter-story isolation structures, scholars have conducted extensive research on inter-story isolation structures in terms of the mass, frequency and damping of the isolation layer. By simulating the constitutive characteristics of the isolation layer and the actual structure, Ying et al. [8] simulated the constitutive characteristics of an inter-story isolation structure. It was considered that the inter-story isolation structure was mainly used to change the natural vibration characteristics of the structure to control the shock absorption. In addition, the energy dissipation of the isolation layer was used to achieve the effects of energy dissipation and shock absorption and the change in the mass ratio also had a significant impact on the shock absorption mechanism. Zheng et al. [9] proposed that the vibration characteristics of buildings depend not only on the stiffness of the isolation layer, building and number of dampers, but also on the stiffness and mass ratio of the superstructure and substructure. Kim et al. [10] analysed the effects of the yield strength and horizontal stiffness of the isolation layer on the displacement. The results showed that an increase in yield strength and horizontal stiffness could effectively reduce the removal of the isolation layer, but it would reduce the stability of the overall structure. Therefore, it is essential to choose reasonable values for the the yield strength and horizontal stiffness of the isolation layer. Faiella et al. [11] concluded from the analysis of two real buildings that the mass ratio of the superstructure to the substructure and the damping of the seismic isolation layer are the main parameters in the design of an inter-story isolation structure. When the stiffness of the isolation layer is small, the inter-story isolation structure can effectively control the seismic response of the superstructure, but it may also amplify the seismic response of the substructure [12]. At this stage, research on the mechanism of inter-story isolation structures is relatively mature. However, the influence of the superstructure on the substructure of the story isolation structure and methods to avoid increasing the seismic response of the substructure are still lacking. Furthermore, the latest design standards for seismic isolation design of buildings promulgated in China provide detailed instructions for the design of inter-story isolated structures and also note that when designing the substructure, the influence of the axial force, bending moment, shear force and additional bending moment generated by the superstructure on the substructure should be fully considered. This indicates that the influence of the superstructure on the substructure cannot be ignored [13]. Wang S J et al. [14] also performed shaking table experiments and found that phase lag exists between the superstructure and substructure; furthermore, the phase lag causes a phase difference between the superstructure and substructure and there are obvious differences in the action of the superstructure on the substructure under different phase differences. The damping effect of inter-story isolated structures under different phase differences is also different. Therefore, the phase difference is a powerful tool for studying the action of the superstructure on the substructure and the seismic dissipation mechanism of the inter-story isolated structure.

Phase is often used to explain the optimal damping effect of a tuned mass damper (TMD). Li [15] proposed that the influence of phase cannot be ignored in TMD system damping analysis. Soong and Dargush [16] discussed the phase concept of a TMD system under simple harmonic excitation. They noted that when the phase difference between the relative displacement of the TMD and the displacement of the main structure was 90 °, the energy transferred from the structure to the TMD system was the largest and the TMD damping effect was the best. Zhang et al. [28] proposed that when the phase difference between the force of the TMD on the structure and the external excitation is 180 °, the force of the TMD on the structure is reduced; however, their research was limited to a sinusoidal load input. Zhang [18] proposed that TMD damping is most effective when the phase difference between the central structure velocity and TMD relative to the central structure displacement is 180 °. The application of phase in TMD analysis has been widely studied, but phase in inter-story isolated structures has not yet been researched in depth. Starting from the phase, this paper discusses the interaction between the superstructure and substructure, as well as the influence of the phase on the damping effect of the inter-story isolation structure. Moreover, we obtain the optimal phase difference to achieve the best damping effect of the structure through analysis and further analyse the damping mechanism of the inter-story isolated structure by combining the phase and energy on this basis.

2. Simplified model of inter-story isolation and phase difference calculation

2.1. Simplified model and dynamic equation

The two-mass point model of an inter-story isolated structure is relatively simple and can reflect the influence of the main parameters on the structure [19]. Moreover, it can visually reflect the phase difference between the superstructure and substructure, which is conducive to the phase analysis of inter-story isolated structures. We consider that because the horizontal stiffness of the isolation layer of inter-story isolated structure is much lower than the horizontal stiffness of the superstructure, the superstructure as a whole is close to a state of translational motion under seismic action, acting approximately as a rigid body. When analysing the dynamic characteristics of an inter-story isolated structure, the isolation layer and the superstructure can be simplified to one mass and the substructure is simplified to one mass alone. The simplified model is shown in Figure 1 [20].

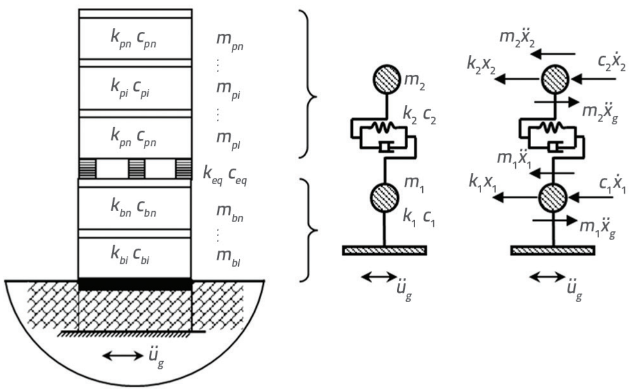

Figure 1. Two-particle model of story isolation structure

The equations of motion are expressed as follows [20]:

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

$$M=\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix},\ C=\begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix},\ K=\begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix},\ I=\begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

where m_1 and m_2 are the equivalent mass of the substructure and total mass of the superstructure, respectively. c_1 and c_2 are the equivalent damping of the substructure and damping of the isolation layer, respectively. k_1 and k_2 are the equivalent stiffness of the substructure and horizontal stiffness of the isolation layer, respectively. x_1 and x_2 are the displacement of the substructure and superstructure, respectively. x_g is the earthquake ground acceleration.

2.2. Phase difference calculation

The acceleration excitation of the substrate was assumed to be P_{sinwt}. Let the right term $\ddot{x}_g$ = P_{sinwt} in Eq. (1). For the simplified model of the inter-story isolated structure, the steady-state solution of the structure is assumed to be

$$\begin{cases} x_1 = A_1\cos\omega t + A_2\sin\omega t \\ x_2 = A_3\cos\omega t + A_4\sin\omega t \end{cases} \tag{2}$$

This is substituted into Eq. (1) and simplified to

$$\begin{cases} A_1(-m_1\omega^2+k_1+k_2)+A_2(c_1+c_2)\omega-A_3k_2-A_4c_2\omega=0 \\ A_1(-c_1-c_2)\omega+A_2(-m_1\omega^2+k_1+k_2)+A_3c_2\omega-A_4k_2=-m_1P \\ -A_1k_2-A_2c_2\omega+A_3(-m_2\omega^2+k_2)+A_4c_2\omega=0 \\ A_1c_2\omega-k_2A_2-A_3c_2\omega+A_4(-m_2\omega^2+k_2)=-m_2P \end{cases} \tag{3}$$

We divide Eq. (3) by and let

$a = -\omega^2 + \omega_1^2 + \omega_1^2 u$, $b = 2\omega\omega_1\xi_1 + 2\omega_2\xi_2 u\omega$

$c = \omega_2^2 u$, $d = 2\omega\omega_2\xi_2 u$, $g = u\omega_2^2 - u\omega^2$

Here, ω_1 is the frequency of the substructure, ξ_1 is the damping ratio of the substructure, ω_2 is the frequency of the superstructure, ξ_2 is the damping ratio of the superstructure and the mass ratio is $u = m_2/m_1$; we solve the quadratic system of equations to obtain the following:

$$A_1=\frac{(bd^2-d^3u-d^3+c^2d+bg^2+bd^2u-c^2du-2cdg+acdu-adgu+bcgu)p}{a^2d^2+a^2g^2-2ac^2g-4acd^2+2ad^2g+b^2d^2+b^2g^2+2bc^2d-4bcdg-2bd^3+c^4+2c^2d^2+d^4}$$

$$A_2=\frac{-(ad^2-c^3u-2cd^2+ag^2-c^2g+d^2g+ad^2u-cd^2u-bcdu+acgu+bdgu)p}{a^2d^2+a^2g^2-2ac^2g-4acd^2+2ad^2g+b^2d^2+b^2g^2+2bc^2d-4bcdg-2bd^3+c^4+2c^2d^2+d^4}$$

$$A_3=\frac{(bd^2-c^2d-d^3+acd-adg+bcg+bc^2u+a^2du-bd^2u+b^2du-2acdu)p}{a^2d^2+a^2g^2-2ac^2g-4acd^2+2ad^2g+b^2d^2+b^2g^2+2bc^2d-4bcdg-2bd^3+c^4+2c^2d^2+d^4}$$

$$A_4=\frac{-(ad^2-cd^2-c^3-bcd+acg+bdg-ac^2u+ad^2u+a^2gu+b^2gu-2bcdu)p}{a^2d^2+a^2g^2-2ac^2g-4acd^2+2ad^2g+b^2d^2+b^2g^2+2bc^2d-4bcdg-2bd^3+c^4+2c^2d^2+d^4}$$

The relative displacement of the superstructure is

$$x_2 = A_r\sin(\omega t + \varphi_r) \tag{4}$$

In Eq. (4):

$$\tan\varphi_r = \frac{A_3-A_1}{A_4-A_2},\ A_r=\sqrt{(A_3-A_1)^2+(A_4-A_2)^2}$$

The substructure speed is

$$\dot{x}_1 = A_a\sin(\omega t+\varphi_a) \tag{5}$$

In Eq. (5):

$$\tan\varphi_a = -\frac{A_2}{A_1},\ A_a=\sqrt{(A_1\omega)^2+(A_2\omega)^2}$$

Then, the phase difference between the relative displacement of the superstructure and the velocity of the substructure is

$$\theta = \varphi_r - \varphi_a \tag{6}$$

3. Phase difference and damping effect

3.1. Relationship between phase difference and damping effect

To study the relationship between the phase difference and damping effect in one cycle, we translate the coordinates of Eqs. (4) and (5) along the time axis direction φ_α/ω, which does not affect the calculation of phase difference, from which the following equation can be obtained:

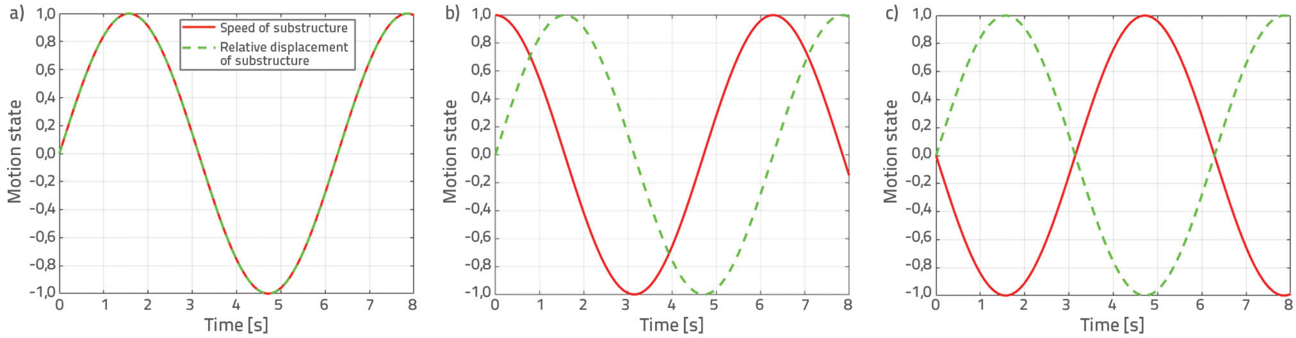

Figure 2. Relative displacement of superstructure and speed of substructure: a)θ = 0°; b) θ = 90°; c) θ = 180°

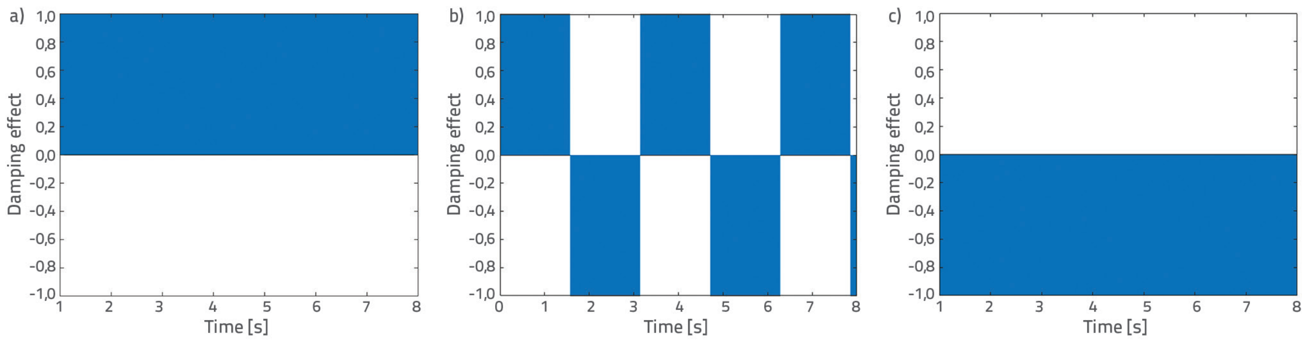

Figure 3. Phase difference and damping effect: a) θ = 0°; b) θ = 90°; c) θ = 180°

$$\dot{x}_1 = A_a \sin(\omega t + \varphi_a - \varphi_a) = A_a \sin(\omega t) \tag{7}$$

$$x_2 = A_r \sin(\omega t + \varphi_r - \varphi_a) = A_r \sin(\omega t + \theta) \tag{8}$$

For convenience of analysis, it is assumed that $A_a = A_r = 1$. Meanwhile, the values of phase difference θ are 0°, 90° and 180°. Figures 2 and 3 are drawn according to Eqs. (6) and (7). These figures illustrate the effect of the phase on the seismic reduction of the structure. The curves with different signs in Figure 2 indicate that the seismic response of the substructure is reduced, whereas curves with the same sign indicate that the seismic response of the substructure is amplified.

Based on the damping scenario illustrated in Figure 2, we plotted the phase difference damping analysis shown in Figure 3, which more intuitively reflects the effect of the phase difference on the damping effect of the structure. From Figure 3, when the phase difference is 0°, the response of the substructure is always amplified; when the phase difference is 90°, the situation is the opposite and the response of the substructure is always decreasing; and when the phase difference is 180°, the time of amplification and decrease in the substructure seismic response in one cycle is half. Therefore, 180° is the optimal phase difference to reduce the seismic response of the structure.

3.2. Phase energy principle

To further verify the correctness of the theoretical analysis in Section 2.1 and to analyse the change in work done by the superstructure on the substructure under different phase differences in one cycle, this study adopted the phase energy principle [21] to combine the phase and work to discuss the effect of the phase difference on the damping effect of the inter-story isolated structure. The expression for the work performed by the superstructure on the substructure is as follows:

$$E_\theta = \int_0^{2\pi/\omega} F_\theta \cdot \dot{x}_1 dt = \int_0^{2\pi/\omega} F_\theta \cdot A_a \sin(\omega t) \tag{9}$$

$$F_\theta = k_2 \cdot x_2 = k_2 \cdot A_r \sin(\omega t + \theta) a \tag{10}$$

In the formula, the elastic restoring force F_θ of the superstructure is taken as the equivalent force of the superstructure to the substructure, $\dot{x}_1$ is the velocity of the substructure, x_2 is the displacement of the superstructure and k_2 is the stiffness of the isolation layer. To obtain the general law, the substructure mass is defined as 1 and the superstructure mass changes with changes in the mass ratio. Using Eq. 8, mass ratios of 0.1, 1 and 20 were selected to draw Figure 4.

From Figure 4, when the phase difference is 0°, the superstructure achieves the maximum positive work on the substructure and amplifies the seismic response of the structure. When the phase difference is ±180 °, the superstructure performs the maximum negative work on the substructure and reduces the seismic response of the structure; when the phase difference is ±90°, the superstructure does work on the substructure and neither amplifies nor reduces the seismic response of the structure. At the same time, comparing the work done under different mass ratios, we can conclude that the larger the mass ratio, the more significant the work done by the superstructure on the substructure. When the frequency ratio is small, the work performed by the superstructure is insignificant. When the

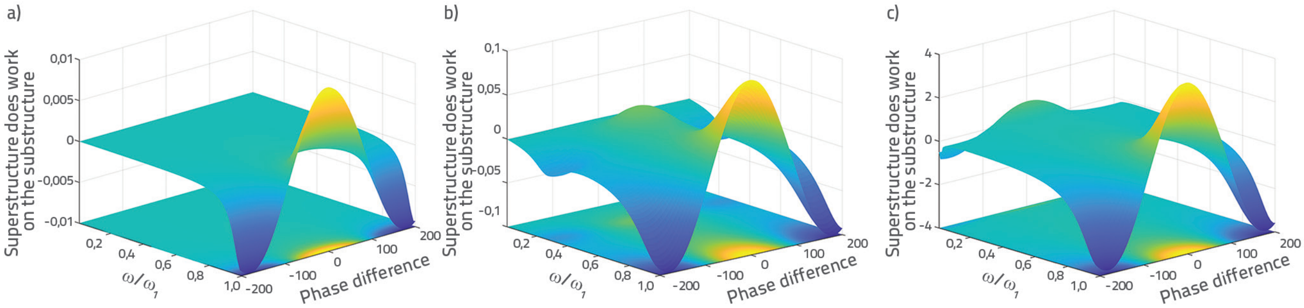

Figure 4. Work done by the superstructure on the substructure: a) Mass ratio of 0.1; b) Mass ratio of 1; Mass ratio is 20

mass ratio is moderate and large, the frequency ratio is close to 0.3 and 0.01, respectively and the work done by the superstructure on the substructure also significantly improved, because the external excitation frequency is close to the self-oscillation frequency of the superstructure and resonance occurs.

4. Phase difference analysis

The phase difference between the superstructure and substructure varies with changes in the structural mass ratio, frequency ratio and damping ratio. Therefore, the selection of the parameters for the inter-story isolated structure is a key issue in studying the phase difference variation [22]. It is important to choose a suitable parameter range to make the phase difference close to 180° for the phase analysis. In this study, we first analysed the variation law of the phase difference within the parameter range of the principle of minimum base shear and then optimised the phase difference as the optimisation objective for the damping ratio of the seismic isolation layer. Based on these results, we studied the effect of the vibration mode on the phase difference.

4.1. Parameter analysis and optimisation

First, an analysis was performed in the parameter range of the principle of minimum base shear [9]. The damping ratio of the substructure is 0.05, the range of the mass ratio u is 0.01–20, the range of the damping ratio of the isolation layer is 0.01–0.5 and the range of the frequency ratio between the superstructure and substructure is 0.01–1.0. The change in the phase difference in the above parameter range was analysed and the damping ratio of the seismic isolation layer was optimised.

The phase difference is not affected by the period change in the substructure, as shown in Figure 5. The phase difference decreases with an increase in mass ratio. The rate of change is faster when the mass ratio is smaller, slower when the mass ratio is larger and gradually tends toward 90°. The phase difference decreases slightly with an increase in the frequency ratio and then increases with an increase in the frequency ratio.. Figure 6 shows the relationship among the phase difference, isolation layer damping ratio and frequency ratio, where the frequency ratio is the ratio of the external excitation frequency to the substructure frequency. The phase difference under different damping ratios first increases and then decreases with an increase in the frequency ratio. When the damping is relatively small, the change rate of the phase difference is faster, whereas when the damping ratio is large, the change rate is slow, as shown in Figure 5.

Because the isolation layer damping ratio is a key issue in the design of inter-story isolation structures, this study used the results shown

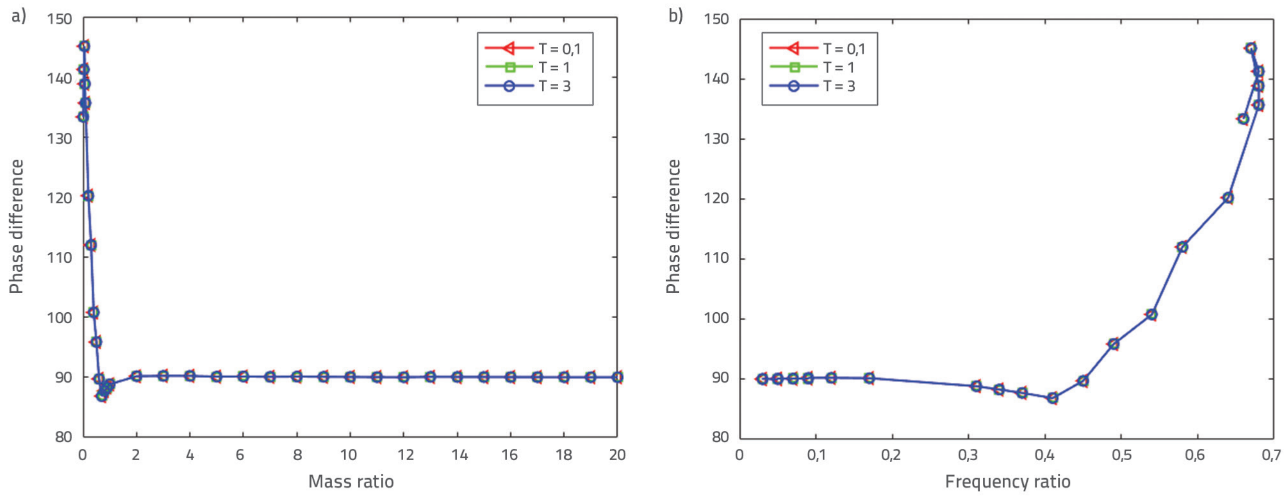

Figure 5. Relationship between phase difference and mass ratio and frequency ratio under different periods: a) Phase difference shift with mass ratio; b) Phase difference shift with frequency ratio

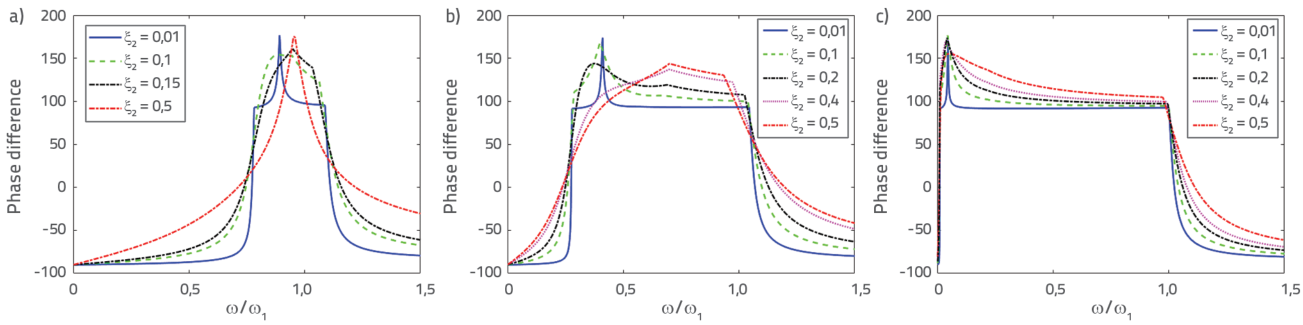

Figure 6. Relationship between damping ratio of seismic isolation layer and phase difference: a) u=0.1; b) u=1; c u=20

in Figure 6 and the influence of the phase difference on the damping effect to optimise the range of the isolation layer damping ratio. For phase analysis, the phase difference at the optimal damping ratio should be close to 180° and the phase difference between 90° and 180° should have a relatively wide frequency band. According to the above principles, we obtained that the optimal damping ratio range is 0.1 to 0.15, 0.2 to 0.4 and 0.1 to 0.5 when the mass ratio is small, moderate and large, respectively.

4.2. Vibration mode analysis

The optimal parameters described in Section 3.1 were selected to plot the first- and second-order vibration coordinates of the simplified model of the inter-story isolated structure, as shown in Figure 7. The upper plane of the figure represents the superstructure vibration coordinates and the lower plane represents the substructure vibration coordinates. The first-order vibration coordinates of the superstructure and substructure are in the same direction and the phase difference between the superstructure and substructure is smaller. The second-order vibration coordinates are reversed and the phase difference between the superstructure and substructure is larger; thus, the phase lag phenomenon is more evident.

Figure 8 shows the relationship between the motion of the superstructure and substructure of the inter-story isolated structure under different vibration modes. The two masses of the first-order oscillation are always in the same phase, whereas the two masses of the second-order oscillation are always in opposite phases.

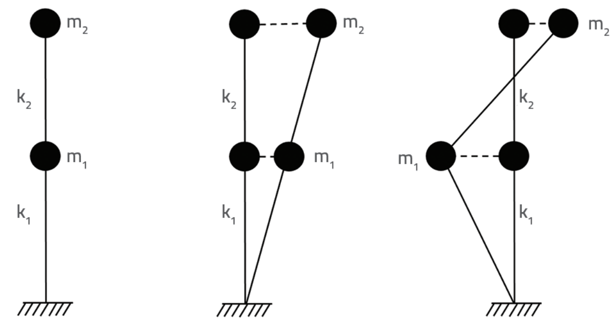

Figure 8. Vibration mode diagram of inter-story isolated structure

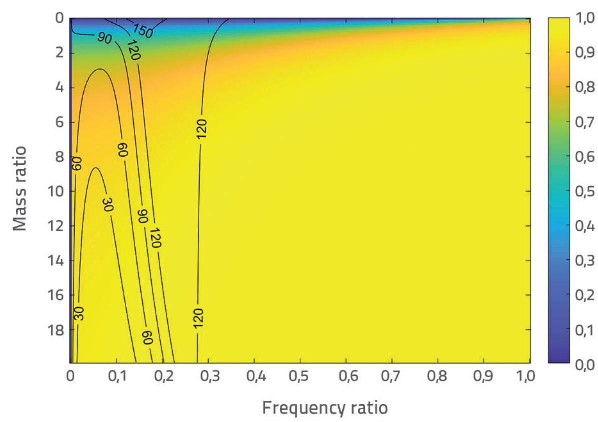

Figure 9. Mass participation coefficient of vibration mode

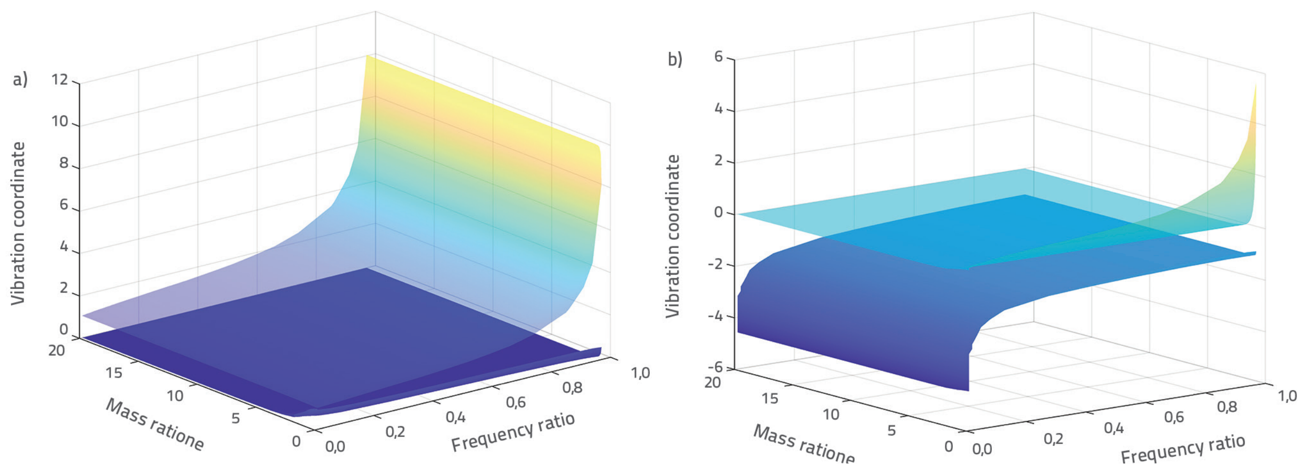

Figure 7. Coordinate changes of inter-story isolation mode: a) First-order vibration coordinates; b) Second-order vibration coordinates

The modal mass participation factor directly reflects the degree of influence of the vibration mode on the seismic response. The two-particle equivalent model has only two vibration modes and the sum of the modal mass participation factors is 1 [23]. Figure 9 shows the relationship between the mass participation coefficient of the first-order mode and the mass and frequency ratios, which reflects the change in the mass participation coefficient of the second-order mode. The contour line in the figure shows the change in phase difference. The diagram shows that the influence of the mass ratio on the mass participation coefficient of the vibration mode is evident, whereas the influence of the frequency ratio on the mass participation coefficient of the vibration mode is small. The first-order vibration mode always has a significant effect on the structure. With a decrease in the mass and frequency ratios, the influence of the second-order vibration mode on the structure becomes increasingly obvious. The variation in the phase difference with the mass and frequency ratios in the diagram is consistent with the change rule shown in Figure 5. Furthermore, the phase difference increases with an increase in the mass participation coefficient of the second-order mode. When the phase difference is closest to 180°, the mass participation coefficient of the second-order mode is relatively large. Therefore, the second-order mode has a significant influence on whether the phase difference between the superstructure and the substructure can be close to 180°.

5. Energy analysis of inter-story isolated structures based on phase

The effects of an earthquake on a structure involve energy transfer, transformation and dissipation. Using energy to analyse the influence of the phase difference on the damping effect can better illustrate response the entire process of the structure under earthquake action and the elastic-plastic performance of the structure itself [24]. In the range of the optimal parameters described in Section 3.1, the processes of energy transfer, transformation and consumption under different phase differences in a cycle were analysed and the influence of the phase difference on the damping effect of the inter-story isolation structure was further studied.

5.1. Energy balance equation of inter-story isolation

When a structure is subjected to an earthquake, part of the total energy input to the structure is stored as kinetic energy and recoverable elastic strain energy and the other parts are consumed by the damping of the structure itself and by irrecoverable inelastic deformation [25]. Based on the model assumptions, a two-mass model was used to establish the energy balance equation for the inter-story isolation structure as follows:

$$E_e + E_p + E_h = E \tag{11}$$

In Eq. (11), E_e is the elastic vibration energy of the inter-story isolated structure, E_p is the hysteretic energy dissipation in the isolation layer, E_h is the damping energy dissipation of the substructure and ***E*** is the total energy input to the structure from the earthquake.

5.2. Elastic vibration energy

Based on the model assumption that the superstructure is rigid and does not generate elastic vibration energy, the elastic vibration energy of the inter-story isolated structure is only affected by the elastic deformation of the isolation layer and substructure [26] and the formula can be expressed by the maximum deformation response of the seismic isolation layer and substructure:

$$E_e = \frac{fQ_m \cdot \delta_2}{2}\left[1 + \frac{m_1}{m_2}\left(\frac{T_1}{T_2}\right)^2\left(\frac{\delta_1}{\delta_2}\right)^2\right] \tag{12}$$

$$\delta_1 = \max\left[-\frac{A_a}{\omega}\cos(\omega t)\right],\ \delta_2 = \max\left[A_a\sin(\omega t) + \frac{A_r}{\omega}\cos(\omega t + \theta)\right] \tag{13}$$

In Eq. (12), fQ_m is the maximum shear force borne by the isolation layer; T_1 is the substructure period; T_2 is the superstructure period; δ_1 is the maximum deformation of the substructure, which is defined as the maximum displacement of the substructure in a period under different phase differences; and δ_2 is the maximum deformation of the isolation layer, which is defined as the maximum displacement of the superstructure relative to the substructure in a period under different phase differences.

5.3. Hysteretic energy dissipation of isolation layer

The hysteretic energy dissipation of the isolation layer is equal to the work done by the yield shear force of the damper yQ_m on the cumulative plastic deformation δ_{pm} [27]. The formula is as follows:

$$E_p = yQ_m \cdot \delta_{pm} \tag{14}$$

Here, the cumulative plastic deformation ratio η_m is defined as the ratio of the cumulative plastic deformation δ_{pm} to the yield deformation δ_{pm} of the damper and the average plastic deformation ratio μ_m is defined as the ratio of the maximum deformation δ_2 to the yield deformation δ_{ym} [28]. Simultaneously, the coefficient n is introduced and its physical meaning is the ratio of the hysteretic energy dissipation of the damper to the work done by the vibration of the maximum deformation of the isolation layer in a week. When the maximum deformation of the isolation layer occurs, n = 2 [29]. Therefore, the relationship between the cumulative plastic deformation ratio η_m and the average plastic deformation ratio can be derived as

$$\eta_m = 4n\bar{\mu}_m \quad (15)$$

The relationship among the hysteretic energy dissipation of the isolation layer, yield shear force of the damper and maximum deformation of isolation layer are established by combining Eqs. (12) and (13):

$$E_p = 4n \cdot yQ \cdot \delta_2 \quad (16)$$

5.4. Damping energy dissipation of substructure

The damping energy dissipation of the frame structure can be obtained using the following empirical formula [30]:

$$E_h = \left[1 - \left(\frac{1}{1 + 3\xi + 1.2\sqrt{\xi}}\right)^2\right] E \quad (17)$$

where E is the total energy input to the structure from the earthquake and ξ is the damping ratio of the structure. Based on the model assumption that the superstructure does not generate damping dissipation energy, the damping dissipation energy of the structure is all provided by the substructure, so the damping dissipation energy can be distributed using the viscous damping dissipation energy of the entire structure without the seismic isolation layer at the same mass ratio. The expressions are as follows:

$$E_h^I = \frac{m_1}{m_1 + m_2} E_h = \left[1 - \left(\frac{1}{1 + 3\xi + 1.2\sqrt{\xi}}\right)^2\right] \frac{E}{1+u} \quad (18)$$

5.5. Effect of phase on inter-story isolation energy

Figure 10 shows the relationships between the percentage of different energies in one cycle and the frequency ratio and phase difference. The frequency ratio is the ratio of the external excitation frequency to the frequency of the substructure. Figure 10 shows that the elastic vibration energy generated by the structure is much smaller than the damping energy of the substructure and the hysteresis energy of the isolation layer. The elastic vibration energy accounts for the smallest proportion of the total energy when the phase difference is close to 0 and 180 ° and the largest when it is close to ±90 °. The hysteresis energy of the isolation layer increases with an increase in the phase difference. The change in

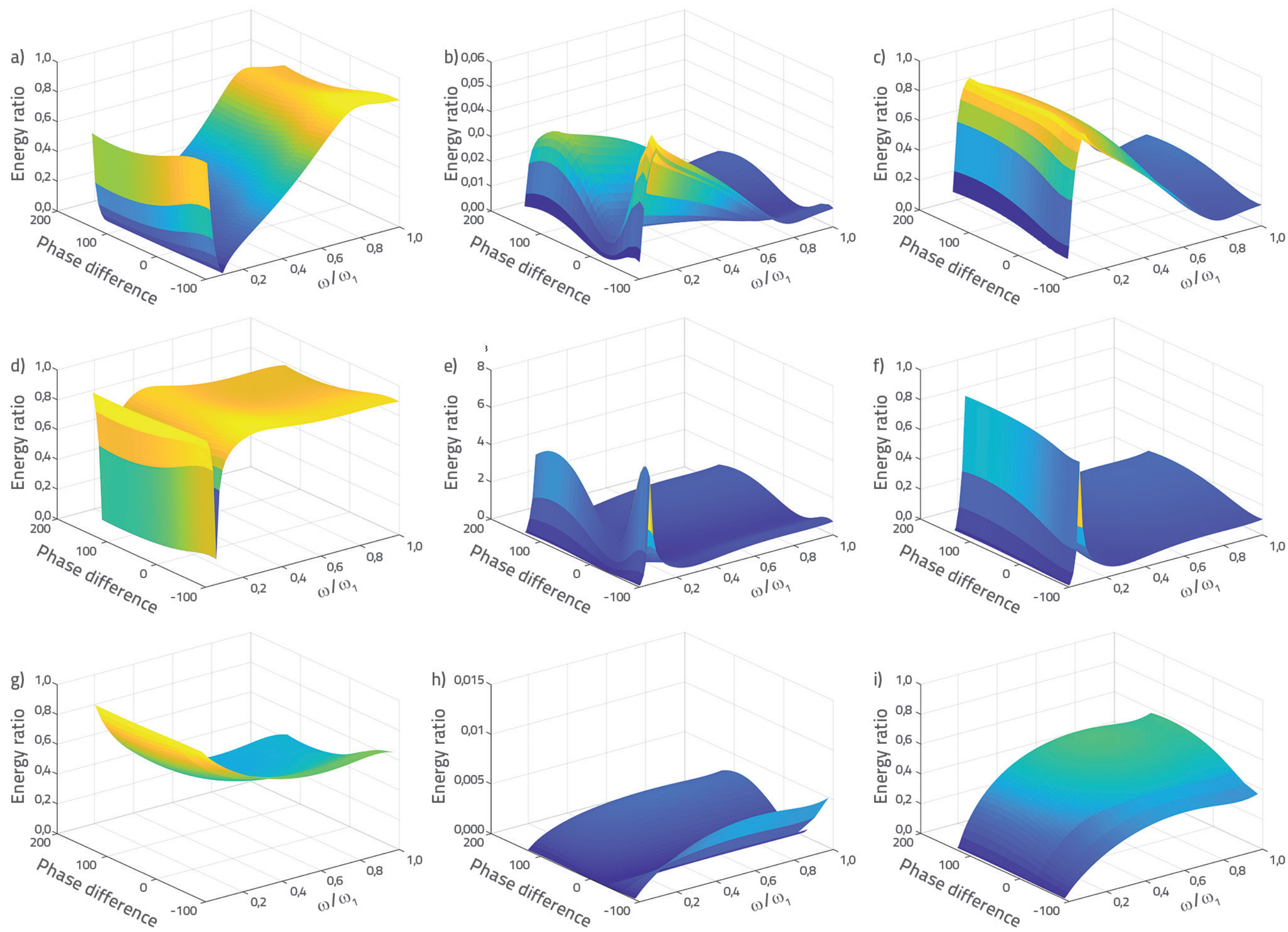

Figure 10. Relation of modal mass participation coefficient to mass ratio and frequency ratio:a) u = 0.1, damping energy dissipation of the substructure; b) u = 0.1, elastic vibration energy; c) u = 0.1, isolation layer hysteretic energy dissipation; d) u = 1, substructure damping energy dissipation; e) u = 1, elastic vibration energy; f) u = 1, isolation layer hysteretic energy dissipation; g) u = 20, damping energy dissipation of substructure; h) u = 1, elastic vibration energy; i) u = 20, isolation layer hysteretic energy dissipation

the damping energy of the substructure with the phase difference is the opposite of the hysteresis energy of the isolation layer, which decreases with an increase in the phase difference. The change in the damping energy of the substructure with the phase difference is the opposite of that of the phase difference, decreasing with an increase in the phase difference. For inter-story isolated structures, the seismic response of the structure can be effectively reduced by using the seismic input energy of the seismic isolation layer and the displacement response of the structure can also be effectively limited through the reasonable control of the elastic vibration energy of the structure. When the phase difference is close to 180°, the transfer, transformation and consumption of energy of the laminated seismic structure are most beneficial to reduce the seismic response of the structure.

6. Conclusion

In this study, we derived a formula for the phase difference between the superstructure and substructure of an inter-story isolation system and optimised the damping ratio of the isolation layer according to the influence of the phase difference on seismic reduction. Furthermore, energy was used to explain the seismic dissipation mechanism the of inter-story isolation structure. The following conclusions were obtained through our analysis:

- When the phase difference between the superstructure and substructure is 180 °, the effect of the superstructure on the substructure can effectively reduce the seismic response of the substructure; when the phase difference is 0 °, the seismic response of the substructure is amplified; and when the phase difference is 90 °, the seismic response of the substructure is neither amplified nor reduced. When the natural frequency of the superstructure or substructure is the same as the external excitation frequency, the influence of the superstructure on the substructure increases.
- To bring the phase difference between the superstructure and substructure close to 180 °, the structural weight ratio can be appropriately reduced and the structural frequency ratio can be appropriately increased. Moreover, the damping ratio of the isolation layer should be selected within the optimal damping ratio range corresponding to the corresponding mass ratio, which is beneficial for reducing the seismic response of the interlayer isolation structure.
- The first-order vibration mode coordinates are in the same direction and the first-order vibration mass participation coefficient decreases with decreases in the structural weight and damping ratios. The second-order vibration mode coordinates are reversed; therefore, the second-order vibration mode contributes significantly to the phase difference, which helps the phase difference between the superstructure and the substructure reach 180 °, thus reducing the seismic response of the structure.
- The analysis of energy transfer, transformation and dissipation can effectively reflect the entire process of the structure under earthquake action, reduce the elastic vibration energy of the structure for the inter-story isolation structure and control the deformation of the structure by using the energy of the isolation layer dissipative structure. Therefore, a phase difference close to 180 ° can not only reduce the seismic response of the substructure, but also control the structural displacement well in the energy analysis.

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