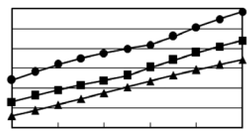
Genetic algorithm optimal arrangement of positive and negative stiffness dampers for hybrid damping based on seismic waves method



Disposición óptima de un algoritmo genético de amortiguadores de rigidez positiva y negativa para la amortiguación híbrida basada en el método de ondas sísmicas

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DOI: http://dx.doi.org/10.6036/9362 | Recibido: 15/08/2019 • Inicio Evaluación: 15/08/2019 • Aceptado: 08/10/2019

RESUMEN

• El aumento de la rigidez negativa puede llevar a un mayor desplazamiento entre capas. Por lo tanto, se debe analizar la influencia de muchos factores entre los amortiguadores de rigidez pseudo-negativa y el desplazamiento entre capas. Con el fin de revelar la relación cualitativa entre la amortiguación híbrida y los parámetros estructurales, se propone un nuevo método que optimiza los parámetros estructurales de los amortiguadores basados en el método de ondas sísmicas con la ayuda de MATLAB y la plataforma funcional SAP2000 OAPI. En primer lugar, un amortiguador de rigidez negativa fue simulado de forma aproximada por la combinación de una unidad de amortiguación paralela y una unidad elástica multilínea, y se investigó el modelo de referencia correspondiente. En segundo lugar, se desarrolló el programa de optimización de la amortiguación estructural de amortiguadores basado en un algoritmo genético. El análisis de optimización de la amortiguación mixta de los amortiguadores de rigidez positiva y negativa se llevó a cabo en el modelo de referencia del bastidor de acero de 20 pisos. La amortiguación de las diferentes rigideces se resumió sobre la base de los resultados de los análisis, y en el estudio se discutió el principio general de disposición del dispositivo en la estructura del edificio. Finalmente, el amortiguador híbrido se formó con el amortiguador de rigidez pseudo-negativo y el amortiguador de rigidez positiva tradicional. El principio de diseño y el efecto de reducción de vibraciones de la amortiguación híbrida se verificaron mediante experimentos con MATLAB y la plataforma funcional SAP2000 OAPI. Los resultados muestran que la aceleración del piso superior de la estructura bajo la acción de la onda El Centro y de la onda de Kobe se reduce en aproximadamente un 15% cuando se utiliza el amortiguador de rigidez pseudo-negativa. Mientras tanto, el desplazamiento de la parte inferior de la estructura se incrementa en sólo un 5%. Además, se pueden obtener mejores resultados de control mediante las diferentes estrategias de control y un análisis exhaustivo de los factores de influencia utilizados en los niveles 2-12 y 13-20. El método propuesto proporciona referencias para optimizar la construcción de plataformas experimentales y la evaluación experimental de amortiguadores híbridos.

• **Palabras clave:** Amortiguador de rigidez negativa, Amortiguación de parámetros estructurales, Pico de desplazamiento entre capas, Algoritmo genético, Optimización de parámetros.

ABSTRACT

Increasing negative stiffness may lead to enhanced interlayer displacement. Therefore, the influence of many factors between pseudo-negative stiffness dampers and interlayer displacement should be analyzed. In order to reveal the qualitative relationship between hybrid damping and structural parameters, a novel method that optimizes the structural parameters of dampers based on based on seismic waves method with the help of MATLAB and the SAP2000 OAPI function platform is proposed. First, a negative stiffness damper was approximately simulated by the combination of a parallel damper unit and a multiline elastic unit, and the corresponding benchmark model was investigated. Second, the optimization program of structural damper damping based on a genetic algorithm was developed. Optimization analysis of the mixed damping of positive and negative stiffness dampers was conducted on the 20-story steel frame benchmark model. The damping of different stiffness was summarized on the basis of the analysis results, and the general arrangement principle of the device in the high-rise structure was discussed in the study. Finally, the hybrid damping was formed by the pseudo-negative stiffness damper and the traditional positive stiffness damper. The layout principle and vibration reduction effect of the hybrid damping were verified by experiments under MATLAB and the SAP2000 OAPI function platform. Results show that the top floor acceleration of the structure under the action of the El Centro wave and Kobe wave is reduced by approximately 15% when the pseudo-negative stiffness damper is used. Meanwhile, the displacement of the lower part of the structure is increased by only 5%. Furthermore, enhanced control results can be obtained by the different control strategies and a thorough analysis of the influencing factors used in layers 2–12 and 13–20. The proposed method provides references for optimizing the experimental platform construction and experimental evaluation of hybrid damping dampers.

Keywords: Negative stiffness damper, Structural parameter damping, Interlayer displacement peak, Genetic algorithm, Parameter optimization.

1. INTRODUCTION

With the continuous development of modern control theory, the damping control of building structures has been rapidly developing in recent years. In particular, scholars have been studying the application of the negative stiffness principle on the damping control of building structures [1-3]. Theoretical analysis has verified that installing a negative stiffness device in a structure can provide the damping ratio of the building structure, thereby enabling the acceleration response of the structure to be con-

trolled under earthquake action [4-5]. Therefore, extending the period of a building structure is an effective means of reducing the acceleration of the structure based on the idea of realizing control without increasing or reducing the structural stiffness. One way to extend such period is to reduce the rigidity of the building structure. Thus, a cascade-structural negative stiffness control method with a positive and negative stiffness damping (NSD) device is proposed. In precision manufacturing, the principle of negative stiffness has also been applied to mechanical vibration control [6-7]. Lemuria H.[1] proposed the use of magnetorheological dampers combined with a specific control algorithm to realize a pseudo-negative stiffness damper and achieve structural NSD. A negative stiffness structural vibration control scheme was also proposed through the development of a NSD component that was combined with ordinary rubber bearings to form a new isolation system.However, the layout of pseudo-negative stiffness dampers in high-rise building structures has not been thoroughly discussed [8-11], especially for the seismic analysis of multilayer steel structures. In light of this issue, with the help of the investigation of Shahadat et al. [12-15], the current study mainly discusses the existence of negative stiffness grade steel structure systems with different properties, such as friction nonlinearity. Accurately determining the acceleration analysis of pseudo-negative stiffness dampers for rigid-structured buildings is an urgent problem.

2. STATE OF ART

Many researchers have studied the trajectory control of control systems with pseudo-negative and positive and negative stiffness dampers. The Grunwald–Letnikov method, which was proposed by R. Scherer et al. [15-20], can qualitatively analyze the stability, convergence, and nonlinearity of differential systems, but the technique is complex and only applicable to fractional-order chaotic systems. Furthermore, Y. Huang [21] considered the approximate free control of a vehicle active suspension with hydraulic actuators, but the time lag effect of the hydraulic actuator and the combined control of the hybrid damping were not examined in detail. C. Hua [21] discussed the unknown semi-dead zone of the control input and proposed the adaptive predetermined performance control of a vehicle active suspension system but did not further explore the combination of acceleration and displacement peaks. Additionally, C. Gorges [23] used a machine learning rough set classification method to detect road bumps, but the quantitative analysis of its damping strategy and anti-vibration mechanism needs in-depth study. J. Zhao [24] realized an automotive variable hydraulic shock absorber and adopted valley search to optimize the PID method. However, the variable coefficient and degree of freedom configuration sequence require further discussion.

In this study, the description function method is used to analyze the nonlinear problems caused by seismic waves or irregular vibrations to achieve hybrid damping in a developed system. The hybrid damper system developed by this study is a 20-story steel frame benchmark model. Such a system is typically significantly different between the 2nd–12th and 13th–20th floors subjected to different seismic wave vibrations and propagation seismic mechanisms; this condition leads to differences in displacement between structural floors caused by the nonlinear friction of such systems [12]. Different control strategies and influence factors need to be analyzed, especially for floors 2-12 and 13-20, to optimize the parameters of pseudo-negative stiffness dampers. In theory, all kinds of complex finite element problems can be deal with the help of Matlab. However the structure is not simplified and the modeling process will be very complex, which does not meet the actual application requirements. In order to avoid the difficulty of complex structure modeling, this paper provides a mixed use of MATLAB and SAP2000 analysis method, In order to solve the above contradictions and make the optimization algorithm widely used in the engineering field, this chapter proposes a very simple way: to model the structure in SAP2000, and to call the SAP2000's open application programming interface (OAPI) in MATLAB with the genetic algorithm function to write the optimization program to optimize the damper layout. In this chapter, a simplified model of a ten story structure and a 20 story steel frame of the second stage benchmark structure are taken as the research objects, respectively. The optimal arrangement of positive and negative stiffness dampers based on genetic algorithm is studied.

The remainder of this study is organized as follows. Section 3 describes the common methods of evolutionary computation and the flow and specificity of the genetic algorithm in the processing of multilayer steel structures. In particular, this chapter analyzes the construction of a mathematical model of the 20-story steel structure as the first-stage benchmark problem. Section 4 studies the vibration reduction optimization of the model with the reference structure and then analyzes the different control strategies and influencing factors of the 2nd-12th and 13th-20th floors. The last section summarizes the study and uses the experimental results to verify the arrangement principle and damping effect of the hybrid damping by pseudo-negative and traditional positive stiffness damper.

3. METHODOLOGY

3.1. SAP2000 NUMERICAL MODEL OF STRUCTURE

3.1.1. 20-STORY STEEL STRUCTURE MODEL

A benchmark model is selected in this study to analyze the third stage of the 20-floor nonlinear steel frame structure. A numerical model is established to provide the mathematical model basis for the succeeding finite element analysis. The size of the structural plane is 30.48 m×36.58 m.Its height is 80.77 m, the east–west span is 6 spans, the north–south span is 5 spans, and the average distance of span is 6.10 m. The height of the two underground floors is 3.65 m, the height of the first floor 5.49 m, and the height of the 2nd to 20th floors 3.96 m. The beam is made of I-shaped steel with a compressive strength of 248 MPa, and the column is made of I-shaped steel with a compressive strength of 345 MPa [10]. The finite element model of the steel structure was established in SAP2000 (Figure 1). The beam and column are made of steel, the floor is made of concrete, and the component dimensions and constraints are set according to the literature [10].

Table I lists the first 10 natural frequencies of the model constructed in this study and compares them with the natural frequency given by the American Society of Civil Engineers (ASCE). The data show a small difference between the two sets of frequencies. Moreover, the shape formed by the first three orders of the structure obtained in SAP2000 is completely consistent with the mode shape given by ASCE. The shape pattern is omitted due to space restrictions. *Table II* lists the seismic response of the benchmark structure under the action of the *El Centro* wave (1940, NS) and the *Kobe* wave (1995, NS). The data show that the results of SAP2000 analysis are considerably similar to those provided by ASCE. In summary, the benchmark model established in SAP2000 is correct and can be utilized as the basis of vibration reduction analysis.

Order	1	2	3	4	5	6	7	8	9	10
SAP2000	0.27	0.75	1.28	1.80	2.35	2.72	3.05	3.32	3.80	4.34
ASCE	0.26	0.75	1.30	1.83	2.40	2.80	3.00	3.21	3.63	4.31

Table I: Natural vibration frequency of the benchmark structure (Unit: Hz)

	El Centro wave (Peak 3.417 m · s $^{-2}$)		Kobe wave (Peak 8.178 m · s $^{-2}$)	
	SAP2000	ASCE	SAP2000	ASCE
Peak displacement /m	0.3203	0.3044	0.5248	0.5173
Peak speed / m · s $^{-1}$	0.9231	0.9157	1.8830	1.8458
Peak acceleration / m · s $^{-2}$	5.4960	5.3392	10.3751	9.9741

Table II: Seismic response of the benchmark structure without control

3.1.2. DAMPER MODEL

The basic concept of stiffness K is the ratio of load increment d*F* and deformation increment d*X* i.e., k = d*F* / d*X*; when the direction of load increment and deformation increment is opposite, it is negative stiffness.The pseudo-negative stiffness damper that needs to be investigated in this work does not have a direct corresponding model in SAP2000.The damping force can be expressed as the following:

$$F[t,x(t)] = cv^{\alpha} + f_N[t,x(t)] \tag{1}$$

$$f_N[t,x(t)] = k_N x(t) \qquad (k_N \le 0) \tag{2}$$

Eqs. (1,2) show that the control force *F [t,x(t)]* of the pseudo-negative stiffness damper can be decomposed into the sum of the ordinary damping force cv^{α} and the negative stiffness control force $k_N x(t)$. On this basis, a damper unit and a linear unit are paralleled in SAP2000 to simulate the pseudo-negative stiffness damper. The stiffness of the linear unit is set to a negative value. If the rigidity of the linear unit is positive, then the damper becomes a conventional positive stiffness damper.

3.2. VIBRATION REDUCTION ANALYSIS OF THE DOUBLE-DEGREE-OF-FREEDOM SYSTEM

When hybrid damping control with the positive and negative stiffness damper is applied to the 20-story steel frame benchmark model, the control strategy should be optimized by double-degree-of-freedom vibration reduction analysis because the degrees of freedom of the 2nd-12th and 13th-20th floors are inconsistent with the control structure[17].

3.2.1. MODEL ANALYSIS OF DOUBLE FREEDOM NSD SYSTEM

After a pseudo-negative stiffness damper is added to a multi-degree-of-freedom structure, the forced vibration differential equation becomes

$$[M]\{\ddot{x}\} + [C_p + C_N]\{\dot{x}\} + [k_p + k_N]\{x\} = \{P(t)\} \tag{3}$$

where C_p and k_p are the damping coefficient and stiffness of the system itself, respectively; C_N and k_N are the damping and stiffness of the negative stiffness damper, respectively, K_N<0. The model shown in Fig. 3 depicts the object of study. C_1, k_{N1}, C_2, and k_{N2} are the negative stiffness damper parameters of the model. x_1 and x_2 are the displacements of the structural and second floors, respectively. The matrices of the structural vibration equation are expressed as follows:

$$[M] = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \tag{4}$$

$$[C_p + C_N] = \begin{bmatrix} C_1 + C_2 & -C_2 \\ -C_2 & C_2 \end{bmatrix} \tag{5}$$

$$[k_p + k_N] = \begin{bmatrix} 2k + k_{N1} + k_{N2} & -(k + k_{N2}) \\ -(k + k_{N2}) & k + k_{N2} \end{bmatrix} \tag{6}$$

First, from the perspective of structural vibration mode, structural damping does not need to be considered. Let the displacement of the structure be:

$$\begin{cases} x_1(t) = X_1 \sin(\omega t - \alpha) \\ x_2(t) = X_2 \sin(\omega t - \beta) \end{cases} \tag{7}$$

Set the two modes of the structure as:

$$\begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{Bmatrix} 1 \\ A_1 \end{Bmatrix} and \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{Bmatrix} 1 \\ A_2 \end{Bmatrix} \tag{8}$$

Eq. (3) is substituted to solve:

$$A_{1,2} = 1 - \frac{1}{2}\left\{1 \pm \left[\sigma^2 + 3\sigma + 4\right]^{\frac{1}{2}}\right\} \tag{9}$$

where $\sigma = \dfrac{k + k_{N1}}{k + k_{N2}}, (\sigma > 0)$.

An analysis of Eq. (9) shows that the displacement response of the upper structure A_1, A_2 must increase with σ. Given that k_N <0, the more noticeable the trend of $|k_{N1}|>|k_{N2}|$, the more beneficial it is for vibration reduction.

3.2.2. VIBRATION REDUCTION ANALYSIS OF NEGATIVE STIFFNESS DAMPER WITH SINGLE-FLOOR ARRANGEMENT

According to Ref. 4, take *m=1x10^{5}kg*, *k=2x10^{7}N/m* in the structure of Fig. 2. When the structure is not set with vibration damping measures, the first two orders of natural vibration frequency correspond to 1.97 and 5.15 *Hz*. The frequency range of the sinusoidal sweep acceleration with a peak input of 2 m/s^2·t is 1-8 *Hz*. With the help of modeling analysis under Simulink, the equation of state in Eq. (10) can be obtained as follow.

$$\begin{cases} \dot{Z}_1 = Z_2 \\ \dot{Z}_2 = \dfrac{-(2k + k_{N1} + k_{N2})Z_1 - (C_1 + C_2)Z_2 + (k + k_{N2})Z_3 + C_2 Z_4 + f(t)}{m_1} \\ \dot{Z}_3 = Z_4 \\ \dot{Z}_4 = \dfrac{(k + k_{N1})Z_1 + C_1 Z_2 - (k + k_{N2})Z_3 - C_2 Z_4 + f(t)}{m_2} \end{cases} \tag{10}$$

First, we analyze the case where a negative stiffness damper is set on only one floor. Let k_{N2}=0N/m, and C_2=4x10^{5}N·s/m (according to Ref. 4). The analysis result is shown in Fig. 1. The stiffness ratio is k_{N1}/k. A ratio greater than zero represents a damper with positive stiffness, and vice versa.

From the results of the above numerical analysis, the following conclusions can be drawn.

(1) With increased first-floor negative stiffness (indicating an increase in absolute value, the same as below), the second-floor acceleration a_2 and the interlayer displacement X_2 are reduced. When the first-floor stiffness ratio is -15%, the second-floor reaction is 10% less than that of ordinary damping.

(2) As the negative stiffness increases, the change of first-floor acceleration a_1 is not remarkable, and nearly no change occurs when the stiffness ratio is between 0% and -20%.

(3) First-floor displacement x_1 increases with the increase of first-floor negative stiffness, but with increased damping coefficient C_1, the growth trend of x_1 gradually slows down. This situation shows that increasing the damping can improve the displacement control effect of NSD.

Table III lists the damping effects of a negative stiffness damper (Case A) in only the first floor and a negative stiffness damper in only a second floor (Case B) to illustrate the effect of the arrangement of the negative stiffness damper on the damping effect of the structure.

The data of A and B in *Table III* show that when the negative stiffness damper is arranged in the second floor, the dynamic response of the structure is noticeably increased, which is not conducive to vibration reduction.

3.2.3. VIBRATION REDUCTION ANALYSIS OF NEGATIVE STIFFNESS DAMPERS WITH TWO-FLOOR ARRANGEMENT

Case 1: A fixed negative stiffness damper with fixed parameters is placed in the first structural floor. Let k_{N1}=-4x10^{6}N/m , and C_1=1.6x10^{6}N·s/m. We discuss the change in the structural vibration response when the second-floor negative stiffness damper parameter changes. The analysis results are shown in Figure 3.

Analysis of the data in Figure 2 reveals the following conclusions.

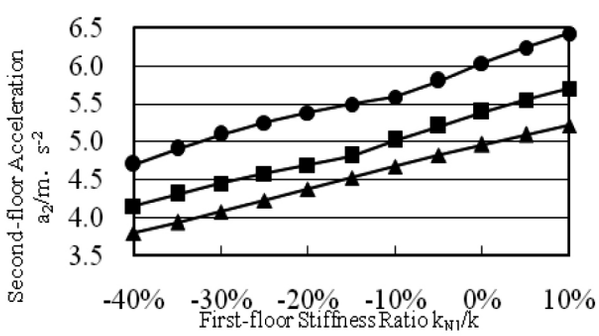
(1) The displacement of the second floor increases significantly with the increase of the negative stiffness ratio of the second floor. When the stiffness ratio is -15%, the displacement of the second floor becomes approximately 12% higher than that of the ordinary damping.

(2) With the increase of the negative stiffness of the second floor, the change of the second-floor acceleration is not evident.

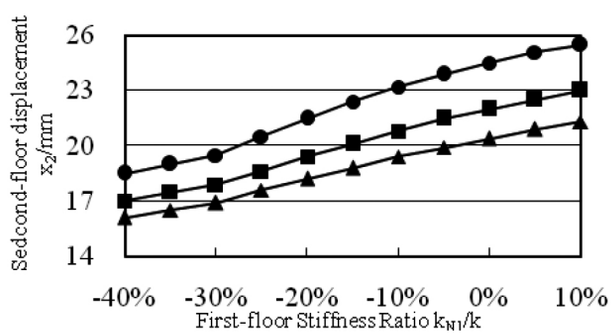
(3) The acceleration and displacement of the first floor decrease with the increase of the negative stiffness of the second floor, but the change is not noticeable. When the stiffness ratio is -15%, the acceleration and displacement of the first floor are reduced by 3% and 1%, respectively, compared with those of the ordinary damping.

Case 2: The same NSD devices are arranged on the upper and lower floors. Let C_1=C_2=1.6x10^{6}N·s/m. We discuss the change of the structural vibration response of the second floor when the stiffness ratio changes synchronously. The results are shown in Figure. 3 (see section: supplementary material).

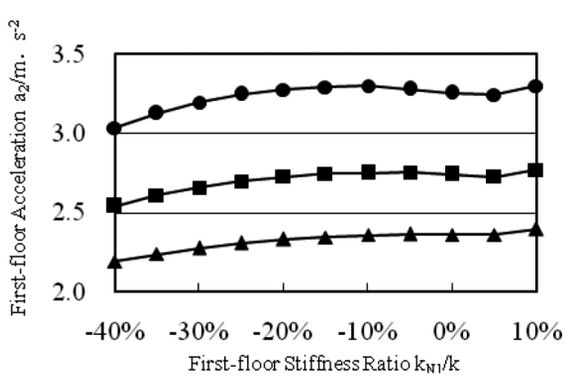
The data in Figure. 3 (see section: supplementary material) reveals that the acceleration response of the structure decreases as



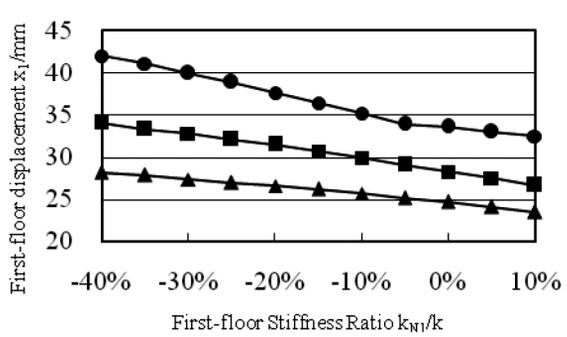
(a) Relationship between the acceleration of the second floor and the stiffness ratio of the first floor



(b) Relationship between the second-floor interfloor displacement and the stiffness ratio of the first floor



(c) Relationship between acceleration and stiffness ratio of the first floor



(d) Relationship between the interfloor displacement and the stiffness ratio of the first floor

-●- $C_1 = 1.2\times10^6 N\cdot s/m$ -■- $C_1 = 1.6\times10^6 N\cdot s/m$ -▲- $C_1 = 2.0\times10^6 N\cdot s/m$

Fig. 1: Relationship between negative stiffness ratio of the first floor and the peak value of the structural response

Case	floor	Stiffness ratio	Damping coefficient 10^5 N·s / m	Acceleration a m / s^2	Interfloor displacement x mm
A	1	-15%	16	2.74	30.7
	2	0	4	4.81	20.1
B	1	0	4	5.01	47.4
	2	-15%	16	6.33	24.4

Table III: Vibration reduction effect when a negative stiffness damper is placed on first or second floors

the stiffness ratio of the second floor decreases, and the interfloor displacement increases as the stiffness ratio decreases. Thus, the negative stiffness device increases the displacement while effectively reducing the structural acceleration response. In addition, the vibration damping effects of the first-floor negative stiffness damper, the second-floor common damper (Case C), and the same negative stiffness damper (Case D) in the two floors are listed in *Table IV*. When the arrangement of Case D is used relative to Case C, the results indicate that the overall acceleration response of the structure decreases, but the interfloor displacement of the second floor increases.

As shown by the above analysis results, the negative stiffness damper should be placed preferentially in the lower part of the structure. If the interfloor displacement meets the requirements, it can also be arranged on the upper part of the structure to further reduce the overall acceleration response of the structure.

3.3. GENETIC ALGORITHM-BASED OPTIMIZATION PROGRAM

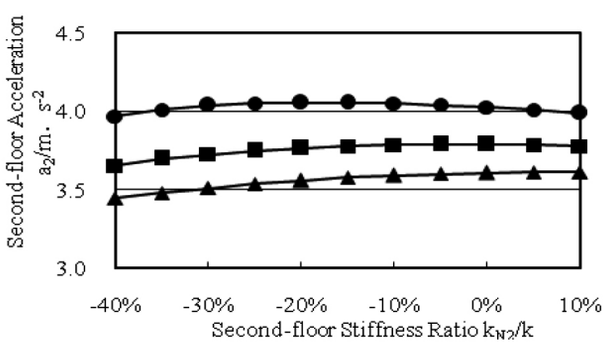
The genetic algorithm belongs to the interdisciplinary disciplines of computer science, intelligent information process, and evolution computing. Its biological basis is the biological evolution of British biologist Darwin. Its optimization process does not need to optimize any information of the object, and it does not depend on the gradient and continuity of the optimized object. Therefore, the genetic algorithm is a robust global optimization algorithm.

3.3.1. OPTIMIZATION PROCESS

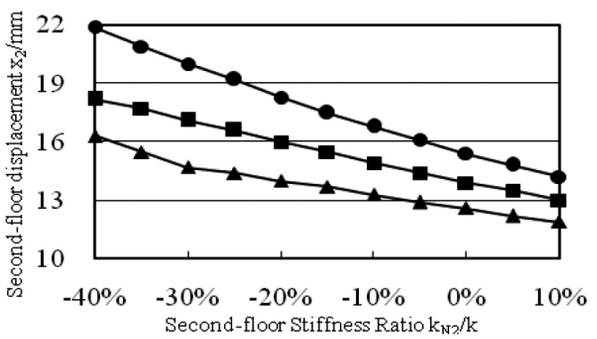
The genetic algorithm optimization function is a built-in feature in MATLAB and can thus be easily used. However, establishing the finite element model of the structure in MATLAB can be cumbersome. Although ASCE provides the stiffness matrix of the benchmark structure that can be used for MATLAB modeling, this issue remains a problem in similar applications for rapid modeling. Therefore, this study builds the benchmark model in SAP2000 and uses MATLAB to call SAP2000's Open Application Programming Interface (OAPI) to analyze the structure. Then, we return the analysis results to MATLAB to complete the optimization of the genetic algorithm. The program flowchart is shown in Figure 4 (see section: supplementary material), where the dotted line is partially completed by SAP2000 and the rest by MATLAB. However, the increase of the negative stiffness in the structure may lead to increased interfloor displacement; moreover, the influence of the pseudo-negative stiffness damper on the displacement between the floors is a key issue considered in this study.

3.3.2. SELECTION OF OPTIMIZATION OBJECTIVE FUNCTION

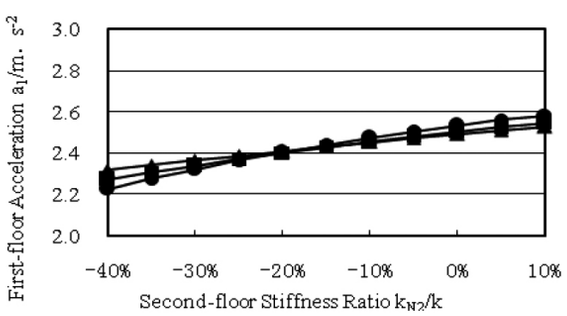
In general, the optimizing design involves three basic elements: design variables, constraints, and objective functions. The design



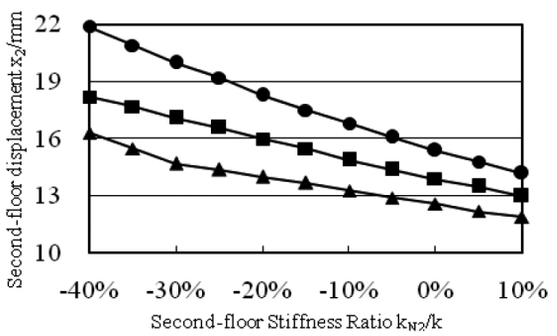
(a) Relationship between acceleration and stiffness ratio of the second floor



(b) Relationship between interfloor displacement and stiffness ratio of the second floor



(c) Relationship between the first-floor acceleration and the second-floor stiffness ratio



(d) Relationship between the first-floor interfloor displacement and the second-floor stiffness ratio

-●- $C_1 = 1.2\times10^6 N\cdot s/m$ -■- $C_1 = 1.6\times10^6 N\cdot s/m$ -▲- $C_1 = 2.0\times10^6 N\cdot s/m$

Fig. 2: Relationship between the second-floor stiffness ratio and the peak response of the structure

Case	Floor	Stiffness ratio	Damping coefficient 10^5 N·s / m	Acceleration a m / s^2	Interfloor displacement x mm
C	1	-15%	16	2.51	28.3
	2	0	16	3.84	14.1
D	1	-15%	16	2.44	28.0
	2	-15%	16	3.83	15.7

Table IV: Vibration reduction effect when a negative stiffness damper is placed on first or second floors

variables in this study are the stiffness values of the dampers. For the sake of generality and comparison with the performance of traditional dampers (positive stiffness) and negative stiffness dampers, the stiffness values of the dampers are allowed to be positive during the optimization process. The reasonable range of stiffness is the constraint of the optimization problem. Given the limited output range of the damper, the optimal range of the damper stiffness is set to -0.3*k* to 0.3*k*, where *k* is the lateral stiffness of the structure. Regarding the objective function, in past approximation studies, scholars have proposed using a linear combination of acceleration, displacement, and other factors (such as the number of dampers and cost) as the objective function. At the same time, the use of the energy relationship as the optimization objective function, which can avoid the problem wherein the optimization results are greatly different due to the selection of seismic waves, has been examined. The optimization objective function of the energy method is

$$\min \quad Z = 1 - \frac{Z_d}{Z_{in}} \tag{11}$$

where Z_d is the energy dissipated by the damper, and Z_{in} is the total input energy of the seismic wave. Adopting this optimization function can avoid the difference between the individual seismic waves and make the shock absorption effect of the same structure on different seismic waves reach a balanced state. The increase of negative stiffness in a structure may lead to increased interfloor displacement. Hence, the influence of the pseudo-negative stiffness damper on the displacement between the floors is a key issue considered in this study. In addition, this work uses the dimensionless dimension of acceleration and interfloor displacement, and the linear combination is utilized as the optimization objective function. The function is

$$\min \quad Z = u_a \frac{a_{\max}}{a'_{\max}} + u_x \frac{x_{\max}}{x'_{\max}} \tag{12}$$

where u_a and u_x are the weight coefficients of acceleration and displacement, respectively. Let $u_a + u_x = 1$; a'_{max} and x'_{max} are constants and denote the maximum acceleration and the maximum interfloor displacement, respectively, of the structure under uncontrolled conditions. a_{max} and x_{max} are the maximum acceleration and maximum interfloor displacement, respectively, of the structure under current conditions. a_{max}/a'_{max} and x_{max}/x'_{max} are the damping rate between acceleration and interfloor displacement.

4. RESULT ANALYSIS AND DISCUSSION

4.1. VIBRATION DAMPING OPTIMIZATION OF RELATED PARAMETERS WITH BENCHMARK STRUCTURE

El Centro wave and the *Kobe* wave are selected as the seismic waves for time history analysis, and the peak acceleration is $6.2m/s^2$ (9 degrees rare). The weight coefficient in the optimization objective function Eq. (1) is shown in *Table V*. For comparison and calculation, the damping index of the damper unit on each floor is regarded as 1. The damping coefficient is the same as that in the literature [11].

As can be seen from *Tables V and VI*, this arrangement is the optimal layout scheme of vibration reduction by damping. The optimization variable in this study is the stiffness value of each floor damper, that is, the stiffness value of the linear unit. Given the limited output range of the damper, the optimum range of the stiffness is set to be $-8x10^7 N/m$ to $8x10^7 N/m$.

4.2. OPTIMIZATION RESULTS AND VIBRATION REDUCTION EFFECTS

The damper stiffness optimization results are shown in Figure5 (see section: supplementary material),. Four optimization calculations are performed using two different seismic waves, and the overall trend is consistent. Therefore, the principle of arrangement of the positive stiffness and pseudo-negative stiffness dampers in the structure can be summarized as follows.

(1) The first floor of the structure should be arranged with a positive stiffness damper. This arrangement is beneficial for reducing the interfloor displacement peak of the structure even when the optimization weight coefficient $k_x = 0$ without considering the interlayer displacement. The first-floor damper stiffness optimization result remains positive.

(2) The damper stiffness of the lower part of the structure's 2nd–12th floors should be negative and gradually increase as the floor increases. The damper stiffness of the upper part of the structure's 13th–20th floors should be positive and gradually increase with the increase of the floor.

To test whether the above optimization results are common and valid, this study selects the El Centro wave, Tangshan wave (1976, EW), and Taft wave (1952, NS) as test samples and then analyzes the structure time history under an acceleration peak value of $6.2m/s^2$. The hybrid damping scheme is the optimization result of Scheme 1. The time history analysis results of El Centro wave and Tangshan wave are shown in Figure. 5 (see section: supplementary material).

The analysis results show that the optimized damper stiffness makes the acceleration of each floor of the structure (except the individual floors) smaller (acceleration peak decreased by approximately 5%) in comparison with that of the ordinary damper with zero stiffness. The interfloor displacement is increased, but the interfloor displacement peak of the entire structure is reduced by about 15%. Under the action of the Taft wave, the same analysis results are obtained.

5. CONCLUSIONS

Method	Seismic wave	K_a	K_x
1	*El Centro*	0.70	0.30
2		0.85	0.15
3		1.00	0.00
4	*Kobe*	0.85	0.15

Table V: List of optimal parameters

Floor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Damping coefficient	7.5	6.5	6.5	6.5	6	6	7	7	6	7	6	5.5	5	5	5	5	4	4	4	4

Table VI: Damping coefficient of each floor (Unit: 10^7 N·s / m)

To explore the optimization characteristics of positive and negative stiffness dampers for hybrid damping, this work reveals the relationship between the stiffness characteristics and acceleration characteristics and interfloor displacement characteristics of positive and negative stiffness dampers. This study starts with the 20-story steel frame benchmark model and uses numerical simulation technology and experimental research to analyze the damping characteristics of different interfloor structures, the acceleration characteristics of steel structures, and the interfloor displacement characteristics of steel structures. The following conclusions could be drawn:

(1) In a high-rise structure, the structural bottom floor shall be provided with a positive stiffness damper, the lower part of the structure shall be arranged with a negative stiffness damper, and the upper part of the structure shall be provided with a positive stiffness damper.

(2) Reasonable arrangement of the pseudo-negative stiffness damper in the structure has an obvious effect (compared with that of the traditional damper) on the control of the structural acceleration and interfloor displacement, but the local interfloor displacement may increase. Thus, the positive and negative stiffness dampers for hybrid damping are better than the ordinary damping scheme.

(3) The mixed programming processing method of MATLAB and SAP2000 proposed in this paper can make full use of SAP2000's modeling advantages and Matlab's optimization analysis function, make intelligent structure analysis more simple, expand the breadth and depth of structure analysis, and provide reference for other similar research. The optimization program based on this method can be used to solve other similar engineering problems.

This study combines laboratory experiments with theoretical research; optimizes the hybrid damping curves with positive and negative stiffness dampers by a genetic algorithm; proposes multilayer steel structures in El Centro, Tangshan (1976, EW), and Taft waves; and reveals the variation law of interfloor displacement and acceleration. The model of positive and negative stiffness dampers for hybrid damping is simplified and close to the actual field, thereby serving as reference for the design of the hybrid vibration reduction, structural design, and subsequent development of high-rise steel structures.

Given the lack of actual data on on-site earthquakes and high-level steel structure monitoring, in future research, interfloor displacement and acceleration monitoring data would be combined with this model for further modification. Additional influencing factors should be considered in future studies. Certainly, this study of positive and negative stiffness dampers for hybrid damping in complex multistory steel structures can improve the accuracy and reliability of future research.

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APPRECIATION

This study was funded by the Government Guiding Regional Science and Technology Development under Grand 2019L3009, the Scientific and Technological Projects of Fuzhou City under Grant No. 2019-G-49 , the Scientific and Technological Projects of Xiamen City under Grant No. 3502Z20179033, the Scientific Research Items of MJU under Grant No. MJY18003.

SUPPLEMENTARY MATERIAL

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