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Research and Application of Negative Stiffness Device in The Field of Earthquake Prevention and Disaster Reduction

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Abstract: The negative stiffness device can reduce the equivalent stiffness of the structure, and has a good control effect on the peak shear force and acceleration response. The combination with the structural vibration theory makes the negative stiffness device fully play its role, and at the same time improves the seismic capacity of the structure, forming a negative stiffness vibration control device. Through reading and sorting out the research achievements of domestic and foreign scholars, the research progress of negative stiffness devices in the field of earthquake prevention and disaster reduction is discussed from the aspects of theoretical development, effect, device application and development trend, and the future development is prospected.

Keywords: Negative stiffness, Vibration control, Structural damping.

1. Introduction

Earthquake is a widely spread and destructive natural disaster that is difficult to predict. The occurrence of earthquakes causes buildings to collapse, terrain to change, and more importantly, it poses a huge threat to people's property safety and health. Damage is particularly prominent in densely populated areas, such as urban areas and industrial areas. At the same time, secondary disasters caused by earthquakes are also difficult to ignore. Tsunamis, plagues, pollution, and other issues are difficult to deal with. Therefore, the study of earthquake causes, earthquake warning, and earthquake protection is a common topic for mankind.

China has a vast territory and a long coastline. Multiple plates, including the Philippine Sea plate and the Pacific plate, compress and interact with each other within our territory, leading to frequent earthquakes in our country and causing great distress to our people. Since 1900[1], there have been as many as 800 earthquakes with magnitudes above 6, and countless earthquakes with magnitudes below 6, causing enormous tragedy. According to statistics, over a hundred years, the number of people killed by earthquakes in China has reached 550000, and more than 300000 square kilometers of land have been affected by disasters. To cope with earthquakes that may strike at any time, improving the seismic capacity of buildings is an effective means to prevent buildings from being damaged and protect people's lives.

2. The Emergence of Structural Vibration Control Theory

The traditional seismic theory mainly improves the stiffness and strength of buildings by optimizing their structures, using high-performance materials, and other means. Its essence is to make buildings rely on their own resistance to earthquake energy and make the failure form of buildings as ductile as possible. However, due to the direct action of seismic energy on buildings, the structure of buildings under the guidance of this seismic theory often produces irreversible damage.

In 1972, Yao[2] first proposed structural vibration control in the civil engineering field. The so-called structural vibration control is to avoid "hard contact" between structures and earthquakes, and instead reduce seismic losses by weakening, transferring, and isolating seismic energy so that it is not sufficient to cause destructive effects on the superstructure. From the perspective of whether external input is needed, structural vibration control theory can be divided into three categories: active control, passive control, and semi-active control. Active control is to control the motion of a structure by inputting external energy to the actuator to respond to different earthquake responses. Common ones include: tuning quality active control system, active anchor cable control system, gas pulse generator control system, etc. The effect of active control is good, especially in recent years, with the development of computing technology, the intelligent control method formed by the combination of vibration control and artificial intelligence is in the ascendant. However, active control requires a large amount of external energy input and has certain requirements for the applicability of the algorithm. Therefore, research on reducing energy requirements and seeking optimal algorithms for active control is still being advanced

Passive control requires no external energy input, and is the addition of a subsystem to the structure to change the dynamic characteristics of the structure. Common ones include[3][4][5][6][7]: foundation isolation systems, energy dissipation and vibration reduction systems, etc. Passive control is an ideal vibration control method due to its simple structure, low cost, and no need for external input. However, how to improve seismic performance while playing a role in earthquakes of different intensities is an urgent problem to be solved.

Semi active control is based on passive control by inputting a small amount of energy to change the parameters of the passive control system to achieve the best results. Common devices include: active variable stiffness devices, active variable damping devices, etc. Semi active control does not require too complex algorithms, and has a low demand for external energy, while the control effect is close to active control, which has high research value.

3. Effect of Negative Stiffness Device

When a structure or component [8] is excited by a load, the increment of force acting on the structure Δ F, and the increment of displacement caused by external loads Δ The ratio of X is called stiffness K. If the ratio of the two is positive, the value is positive, indicating positive stiffness; Conversely, if it is negative, it is negative stiffness. A negative stiffness device is one in which the stiffness of the device added to the structural system is negative.

Whether passive vibration control or active or semi-active vibration control, it needs to rely on corresponding devices to achieve, and the use of most devices often increases the equivalent stiffness of the structure. The stiffness assembly increases the natural frequency of the structure and makes it difficult to control the acceleration response. The negative stiffness device can reduce the equivalent stiffness of the structure, thereby reducing the natural vibration period of the structure, and also has a certain control effect on the peak value of interlayer shear.

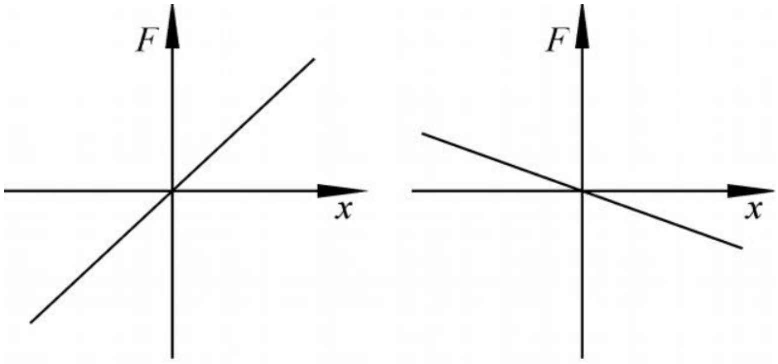

Figure 1. Force displacement curve of positive stiffness device (left figure) and negative stiffness device (right figure)

However, simple negative stiffness devices do not have the ability to dissipate and isolate seismic energy, and have a certain promotional effect on structural displacement. Therefore, combining negative stiffness devices with vibration control theory and combining the advantages of both, it can reduce the structural stiffness while improving the seismic capacity of the building. Because the essence of negative stiffness devices is to change the motion state of structures under earthquake loads, and active vibration control systems have the function of regulating and controlling the motion of structures, the combination of negative stiffness devices and vibration control theory often takes the form of passive control or semi-active control.

4. Research on Negative Stiffness Vibration Control Device

The study of the negative stiffness principle originated in the field of machinery. WG Monyneaux[9] proposed an ideal vibration isolation support model with zero stiffness to solve the interference of vibration on machinery. In this paper, the negative stiffness principle was first proposed to be applied to equipment vibration isolation. Since then, in the field of machinery[10][11][12], negative stiffness devices have received a large number of scholars' attention and research.

4.1. 4.1 Semiactive negative stiffness control

Initially, the introduction of the concept of negative stiffness into the field of earthquake prevention and disaster reduction began with the study of bridges. In 2003, H Iemura[13] proposed a variable damper pseudo-negative stiffness control strategy, which was applied to study the seismic response of cable-stayed bridges. It was found that the damping effect under pseudo-negative stiffness control was close to that of active control. This is an attempt to introduce negative stiffness control into the field of earthquake prevention and disaster reduction, but because this study is limited to simulation, it is inevitable that there are some discrepancies with actual results. Later, H Iemura[14] proposed a simplified semi-active control algorithm in 2005, which only concerns the displacement and velocity of dampers. The resulting negative stiffness output makes the structure exhibit nearly perfect plastic force deformation characteristics. In the performance study of cable bridges under semi-active negative stiffness control, Hui Li[15] proposed indicators to quantify the degree of negative stiffness.

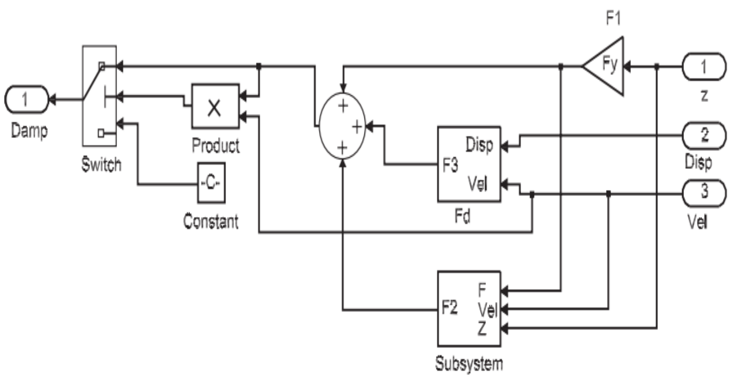

Figure 2. Control flow in H Iemura simulation

Subsequently, some scholars compared negative stiffness control with pure passive control, proving that the control effect of the former is far superior to the latter. In 2009, Shi Pengfei[16] conducted a study on the dynamic characteristics and damping effects of pseudo-negative stiffness damping structures, and compared them with viscous damping structures. He found that the use of pseudo-negative stiffness control extended the equivalent period of the structure. When the structure period was longer, pseudo-negative stiffness damping structures had better control effects on absolute acceleration, but weaker control on relative displacement than viscous damping structures. Based on evolutionary algorithms, C Boston[17][18] studied the optimal control of a negative stiffness variable damping device and applied it to a tuned mass damper. Numerical simulation shows that its effectiveness is superior to that of traditional tuned mass dampers. F Weber[19] has studied the performance of a negative stiffness viscous damper under semi-active control based on C Boston, and it has been proved that the superior damping performance of the device comes from the promotion of negative stiffness on the motion of the damper. Wu Bin[20] studied the flutter problem of pseudo-negative stiffness damping in numerical analysis, revealing the homogeneity of pseudo-negative stiffness control systems, and proving that pseudo-negative stiffness control is superior to passive control in terms of response spectrum, time delay, and stability.

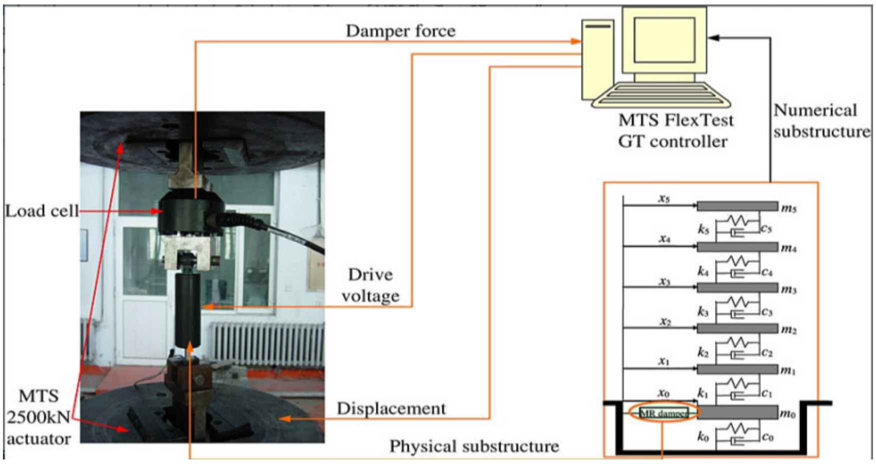

Figure 3. Schematic Diagram of Wu Bin's Real time Hybrid Test of Pseudo negative Stiffness Control

In recent years, the emergence of magnetorheological damping devices has opened up a new direction for the research of semi-active negative stiffness control. MH Pradono[21] applies a negative stiffness device to an inductive magnetorheological damper, which dynamically adjusts the voltage input of the device at different stages of an earthquake to change the magnitude of the damping without actively changing the voltage. The device operates in a manner similar to passive negative stiffness control. J Høgsberg[22] proposed an adaptive control strategy for applying voltage to a semi-active magnetorheological damper, introducing negative stiffness to improve damping performance. Wei Shuli[23] proposes a modified hyperbolic tangent model for realizing negative stiffness control of Magnetorheological Dampers, and uses piecewise linear interpolation based on the model to achieve real-time damping force tracking. Gong Wei[24] has developed a magnetorheological fluid damper based on a pseudo-negative stiffness control algorithm, with a maximum output of 10kN. It exhibits good energy dissipation capacity under frequent, fortified, and rare earthquakes.

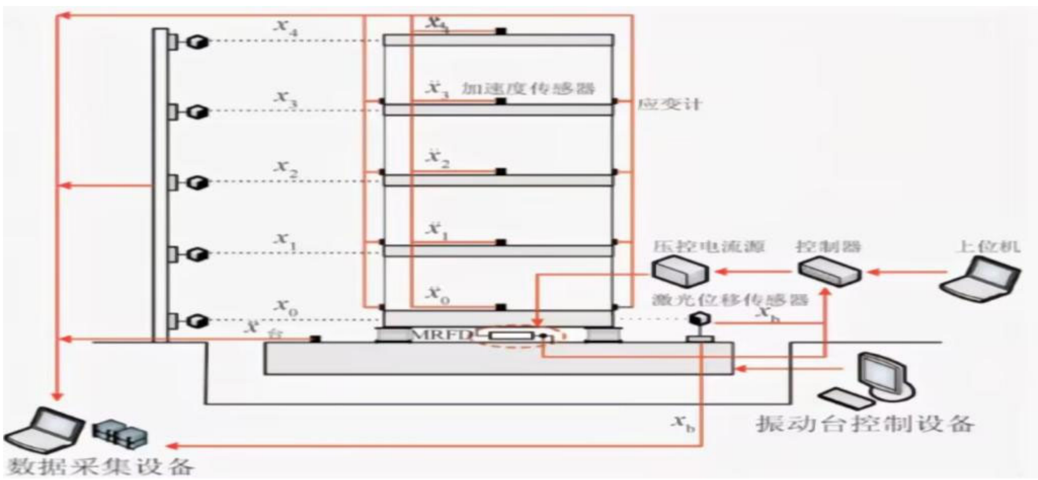

Figure 4. Gong Wei's Structure Control System and Test Data Measurement System

Research has shown that negative stiffness devices exhibit good adaptability in combination with semi-active control. Compared to simple semi-active control and passive control, semi-active negative stiffness control exhibits superior performance in multiple aspects, and as research progresses, the two will exhibit diverse collaborative approaches.

4.2. Passive negative stiffness control

Passive negative stiffness control started relatively late, but has become the mainstream of research in recent years. Passive negative stiffness control originated from the research of S Nagarajaiah[25] in 2010, who developed an adaptive negative stiffness device that can change stiffness based on device displacement without requiring external input.

By combining with various passive control methods, passive negative stiffness control forms different types.

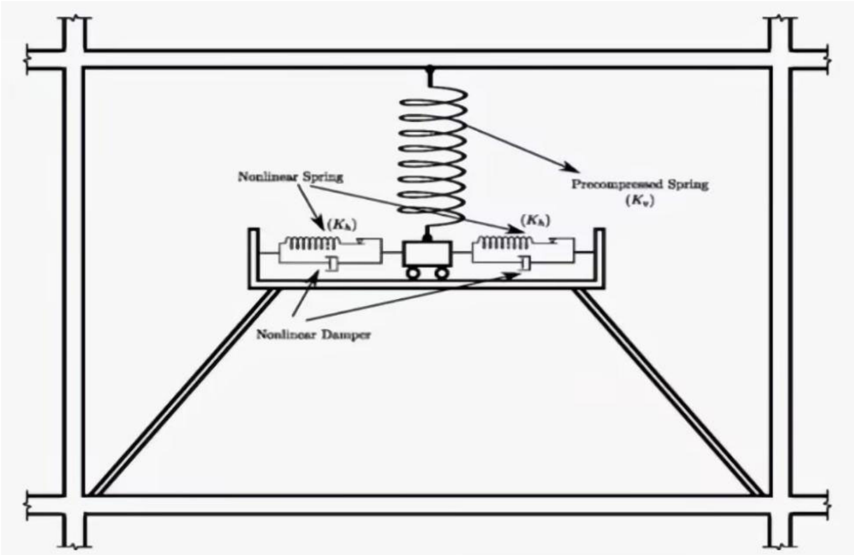

Figure 5. Adaptive negative stiffness device developed by S Nagarajaiah

4.2.1. Viscous negative stiffness control

Viscous negative stiffness control is the introduction of negative stiffness devices into viscous damping structures. The combination of negative stiffness devices with viscous dampers is the beginning of research on passive negative stiffness control.

X Shi[26] combines a viscous damper and a magnetic negative stiffness spring to install on the transverse cable of a cable-stayed bridge, which not only has a superior vibration reduction effect compared to using only viscous dampers, but also improves the bending stiffness of the cable. AA Sarlis[27] combines a pre compressed spring and a clearance spring mechanism to form a passive spring negative stiffness device, and then parallels the device with a viscous damper to simulate the weakening of the structural system without causing inelastic deformation. Liu Wenguang[28] has developed a damping negative stiffness isolation device with viscosity, using a traditional lead rubber bearing isolation system and an isolation system with negative stiffness device to compare and analyze an actual high-rise building. It is found that the effect of the isolation system with negative stiffness is more prominent.

Figure 6. Negative stiffness isolation device developed by Liu Wenguang

Liu Tao[29] proposed a passive variable stiffness isolation bearing with three stages of deformation, consisting of a negative stiffness spring assembly, viscous dampers, and rubber bearings, which are effective for both lateral and vertical vibrations. Yang Qiaorong[30] developed a curved track negative stiffness isolation device based on the background of nuclear power plant isolation. After adding viscous dampers, the hysteretic curve of the isolation layer presents a nonlinear trend of small in the middle and wide at both ends. Compared with traditional power plant isolation designs, the effect is better.

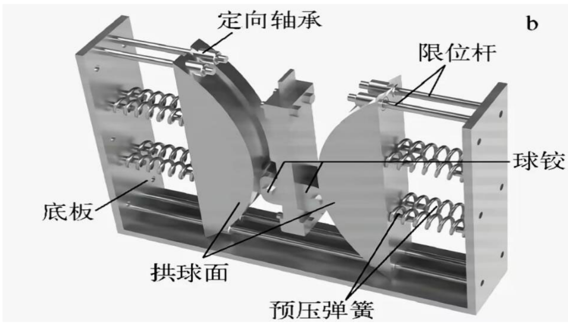

Figure 7. Negative stiffness isolation device for curved track

4.2.2. Friction type negative stiffness control

Friction negative stiffness control is a combination of a negative stiffness device and a friction damper. This device usually has the characteristics of simple structure, low cost, and stable performance.

Chen Y[31] has designed a nonlinear energy absorption device that exhibits negative stiffness, connecting a spring to a mass, and consuming energy using the sliding friction of the mass. It exhibits high efficiency in reducing structural response. Fang Guowei [32] avoided the problem of negative stiffness friction damping devices in building layout and distribution, and proposed a negative stiffness friction damping device arranged at the bottom of the building. This device has simple structure, low cost, and stable mechanical performance. Sun Tianwei [33] combines a nitrogen spring with a translational friction damper to increase the overall negative stiffness output and reduce the peak shear force.

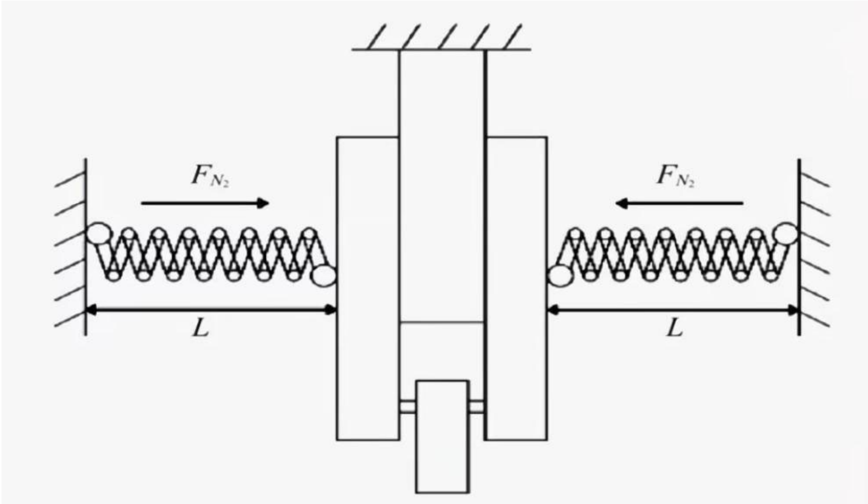

Figure 8. Negative stiffness friction damper developed by Sun Tianwei

4.2.3. Tuned negative stiffness control

Tuned negative stiffness control combines a negative stiffness device with a tuned mass damper to improve the performance of the latter.

In order to solve the problem of mismatch between the frequency of the tuned mass damper and the natural frequency of the structure, Wang Zhihao[34] attached an inertial flywheel and ball screw mechanism that had an apparent negative stiffness effect to the tuned mass damper, which played a good role in adjusting its frequency. Chen Yangyang[35] introduced a negative stiffness device into a nonlinear energy trap, which produces a more significant and sustained instantaneous internal resonance capture behavior on the main structure than traditional tuned mass dampers. Yin Guangzhao[36] proposed a magnetically induced negative stiffness eddy current inertial mass damper. Compared to displacement type negative stiffness devices, the negative stiffness output exhibits a "quasi constant" behavior, which is conducive to structural stiffness parameterization.

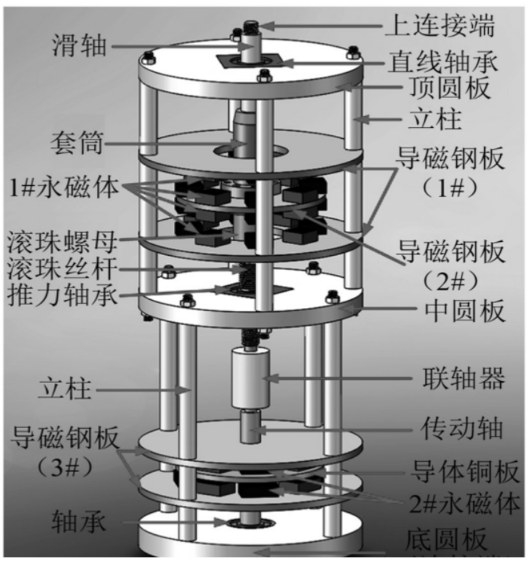

Figure 9. Magnetically induced negative stiffness eddy current inertial damper

4.2.4. Negative stiffness control combined with metal dampers

This form of negative stiffness control is rarely studied. It is more classic for Sun Tong[37] to combine SMA metal dampers with the developed rail type negative stiffness device, which reduces the bottom shear force while also limiting the midspan displacement.

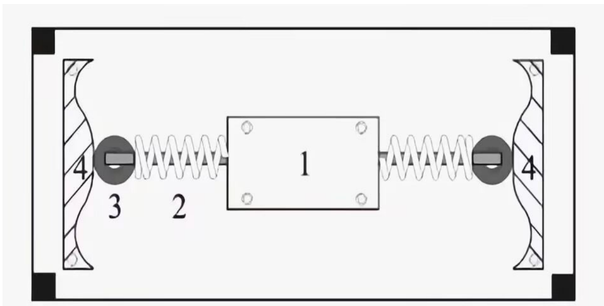

Figure 10. Rail mounted SMA negative stiffness device

5. Summary

This article focuses on the combination of negative stiffness devices and vibration control theory in the field of earthquake prevention and disaster reduction, and expounds the development of vibration control theory, the effect of negative stiffness devices, and the research on negative stiffness vibration control devices. From the perspective of results, negative stiffness devices have significant effects on reducing structural acceleration responses and shear forces, and exhibit good coordination and plasticity in combination with vibration control theory, enabling vibration control devices with negative stiffness characteristics to achieve an effect of "1+1" greater than "2".

Considering the increasing seismic requirements brought about by the rapid development of society and the superior performance of negative stiffness vibration control devices, the research on negative stiffness vibration control is potential and necessary.

Based on existing research, there are several prospects for negative stiffness control:

(1) The biggest obstacle to the practical application of

negative stiffness devices is still the problem of insufficient negative stiffness output, which is urgently needed to be resolved in the process of application.

(2) Passive negative stiffness control is the mainstream of research, but it does not mean that semi-active control is not popular. At least for now, semi-active control still has advantages that the former does not have.

(3) The quantification and parameterization of negative stiffness plays an important role in the subsequent development of negative stiffness control.

(4) The full-scale test of most negative stiffness control devices is difficult, and the simulation results may deviate from the actual situation to some extent. More reasonable and accurate test methods should be explored.

(5) The energy dissipation capability of negative stiffness control is limited by energy dissipation devices such as dampers, and the development and optimization of such devices can promote the effectiveness of negative stiffness control.

(6) The integration of negative stiffness devices and vibration control devices needs to be further promoted.

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