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A CRITICAL REVIEW ON ENERGY DISSIPATER CONTROL STRATEGIES FOR STRUCTURAL VIBRATION CONTROL

KRITIČKI PREGLED STRATEGIJA UPRAVLJANJA DISIPACIJOM ENERGIJE ZA KONTROLU VIBRACIJA KONSTRUKCIJA

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Keywords
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- vibration mitigation
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- passive dampers
- earthquake loads
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Ključne reči
- pasivno upravljanje
- ublažavanje vibracija
- disipacija energije
- pasivni prigušivači
- opterećenja zemljotresa
- bezbednost konstrukcije

Abstract

Passive control is one of the oldest systems of structure safety against dynamic loads. This strategy offers a structural protection using passive devices without needing any energy source or automation. Around the world, several of structures and tall buildings are equipped by these control devices. The passive control consists of a passive device superposed onto the main structure to improve the flexibility or damping. Therefore, during earthquake or wind excitation the additional devices absorb or reduce the caused shock and vibration of the structure. However, the literature is full of studies and investigations on the passive control application in the civil engineering area. Several of these investigations consider the effectiveness of energy dissipater devices to overcome structural disaster during earthquake loads. The main focus of the paper is to discuss the state-of-the-art of the passive control energy dissipater system. Different passive devices are described and the robustness in mitigating of earthquake structural vibration is discussed.

Izvod

Pasivno upravljanje je jedan od najstarijih sistema za bezbednost konstrukcija protiv dinamičkih opterećenja. Ova strategija pruža zaštitu konstrukcija primenom pasivnih uređaja koji ne koriste izvor energije ili automatiku. Nekoliko konstrukcija u svetu, na primer visoke zgrade, poseduju ove upravljačke sisteme. Pasivno upravljanje se sastoji iz pasivnog uređaja koji se montira na glavnu konstrukciju radi poboljšanja fleksibilnosti ili prigušenja. Stoga, pri zemljotresu ili opterećenju od vetra, dopunski uređaji apsorbuju ili redukuju izazvani šok i vibracije na konstrukciji. U literaturi postoji mnogo studija i istraživanja o primeni pasivnog upravljanja u oblasti građevinarstva. Neka istraživanja razmatraju efikasnost ovih uređaja za disipaciju energije, kako bi se sprečile katastrofe prilikom opterećenja od zemljotresa. Cilj rada je diskusija tehnički najnaprednijih sistema pasivnog upravljanja disipacijom energije. Opisani su razni pasivni uređaji i data je diskusija robusnosti u smanjenju vibracija konstrukcija prouzrokovanih zemljotresom.

INTRODUCTION

In the realm of civil engineering structures, seismic activity presents a significant threat, often resulting in substantial damage. One such instance occurred in Antioch, in May 526 A.D., when an earthquake measuring 7 degrees on the Moment magnitude scale ravaged the city, with devastating consequences extending into Syria and Palestine, claiming the lives of over 250,000 individuals /1, 3/. Similarly, in Gaziantep, Turkey, on February 6th 2023, an earthquake registering 7.8 degrees on the Richter scale led to the loss of 51,000 lives /2/. In response to these tragic events, a significant focus of research has been directed towards the advancement and refinement of seismic-resistant construction techniques to mitigate such losses. Over the preceding decades, structural control strategies have garnered substantial attention in scientific inquiry, manifesting in three primary classes: passive, active, and semi-active. Passive control represents the earliest of these methodologies, tracing its origins back through history. Historical records and architectural monuments worldwide attest to the utilisation of passive control principles, such as the Bacchus Temple in Baalbek, Lebanon, constructed around 300 B.C., employing seismic isolation techniques that endure to this day. The passive control approach typically involves the integration of simple devices within the primary structure, devoid of external energy sources or automation. These devices harness the motion of the main structure to generate control forces, whether through isolation, dissipation, or transformation mechanisms /5/.

In the context of seismic isolation, passive devices play a pivotal role in isolating the structure from seismic excitation. Through mechanisms such as friction or sliding, these devices facilitate the rigid-body movement of the structure, thereby minimising structural vibrations. Among the array of seismic isolation devices utilised in civil engineering structures, the lead-elastomer base stands out as one of the most prevalent (Fig. 1). Furthermore, energy transformation devices serve as passive mechanisms integrated into structures to convert earthquake energy into the kinetic energy of structural motion. This technique effectively mitigates structural vibrations, preventing resonance. A prominent example of such energy transformation devices is the tuned mass damper (Fig. 2). Conversely, dissipater devices, operating in a passive mode, absorb seismic energy, predominantly through mechanical or thermal dissipation mechanisms. In the realm of civil engineering structural vibration applications, various dissipater devices find utility /6/.

Figure 1. Lead-elastomer seismic isolator.

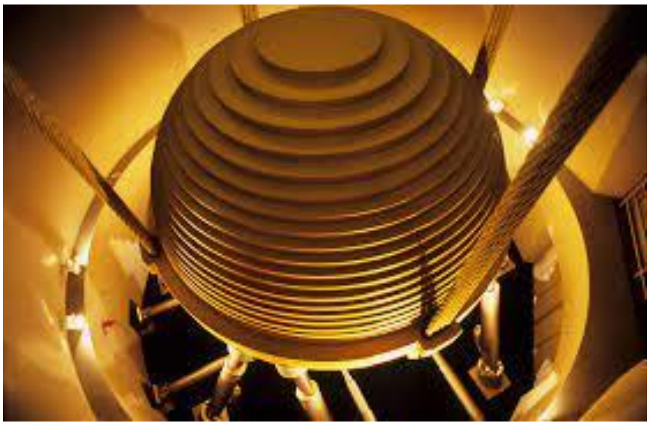

Figure 2. Taipei 101 tuned mass damper.

The main objective of this paper is to present and investigate the dissipater passive control devices in critical study. Based on experimental studies and practical applications a review is extracted.

PASSIVE DISSIPATER ENERGY DEVICES

Hysteretic dissipation energy emerges as a highly effective method for passive structural control within the domain of civil engineering. This strategy leverages the phenomenon of hysteresis, wherein loading and unloading curves exhibit discernible shifts during cyclic loading. As the structure undergoes loading, energy is imparted onto it; however, not all of this energy is recuperated during unloading, leading to a dissipation of energy in the form of heat. A diverse array of energy dissipation mechanisms has been developed and incorporated into structures globally to augment their seismic resilience. These devices have been extensively utilised in buildings and bridges, whether in newly constructed projects or those undergoing renovation, spanning continents such as North America, Asia, and Europe. Prominent examples of such devices abound in both scholarly literature and engineering practice.

METALLIC YIELD DAMPERS

The foremost mechanism for efficiently dissipating energy to a structure subjected to seismic activity resides in the utilisation of metallic yield dampers. These dampers primarily rely on the phenomenon of inelastic deformation exhibited by metals, as illustrated in Fig. 3. Typically fashioned from mild or alloy steel, these shock absorbers assume various geometries, including triangular, X-shaped, or even honeycomb configurations, among others. Such devices demonstrate consistent and predictable hysteresis behaviour, a crucial attribute ensuring reliable energy dissipation across seismic events, resistance to ambient temperature, reliability, and the fact that practically the behaviour of the material used is very well known and very well characterised, /8, 9/.

Figure 3. Application of metallic yield damper in a building.

The damper offers additional stiffness to the structure given by Dargush and Soong /4/,

$$K = cne\left(\frac{b}{l_0}\right)^3 E, \qquad (1)$$

where: c is experimentally given stiffness coefficient; n is plate number; e, b and l_0 are plate dimensions; and E is the Young's modulus.

Under sinusoidal displacement with amplitude of 1.5 cm and a frequency of 2.5 Hz applied to the device, the generated force function of damper displacement is illustrated in Fig. 4.

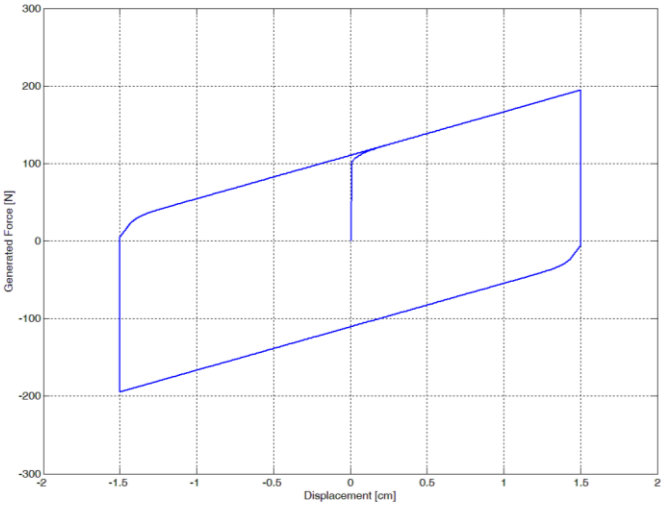

Figure 4. Simulated force-displacement loop of the metallic yield damper under sinusoidal displacement.

FRICTION DAMPERS

These shock absorbers demonstrate exceptional efficacy and durability owing to their capacity to return to their initial position undamaged. Illustrated in Fig. 5, friction dampers employ a mechanism reliant on solid friction between two bodies sliding relative to each other, facilitating energy dissipation through the removal of frictional heat. Under dynamic excitation, this mechanism induces sliding in both tension and compression directions, resulting in the generation of hysteresis loops akin to Coulomb friction behaviour. Depending on the excitation bandwidth, these dampers exhibit adaptability without necessitating tuning, thus offering versatile applicability across various structural contexts /7, 11/.

Figure 5. Friction damper application in steel farm structure.

According to the study by Matsagar and Jangid /10/ the generated control force f_f is given by

$$f_f = k_f x_b + c_f \dot{x}_b \,, \tag{2}$$

where: k_f and c_f are damper stiffness and damping expressed as

$$k_f = \frac{f^+ - f^-}{\Delta^+ - \Delta^-} \,, \tag{3}$$

$$c_f = 2\beta_f m \omega_f \,, \tag{4}$$

where: f^+ and f^- are positive and negative forces of the respective displacement test Δ^+ and Δ^- ; β_f, m and ω_f are effective damping ratio, mass, and effective pulsation given by

$$\omega_f = \sqrt{\frac{m}{k_f}} \,. \tag{5}$$

The effective damping ratio is expressed by

$$\beta_f = \frac{2}{\pi}\left[\frac{E_{cyc}}{k_f\left(|\Delta^+| + |\Delta^-|\right)^2}\right], \tag{6}$$

where: E_{cyc} is dissipated energy by a loading cycle.

Under a sinusoidal displacement with amplitude of 1.5 cm and a frequency of 2.5 Hz applied to the device, the generated force function of damper displacement is illustrated in Fig. 6.

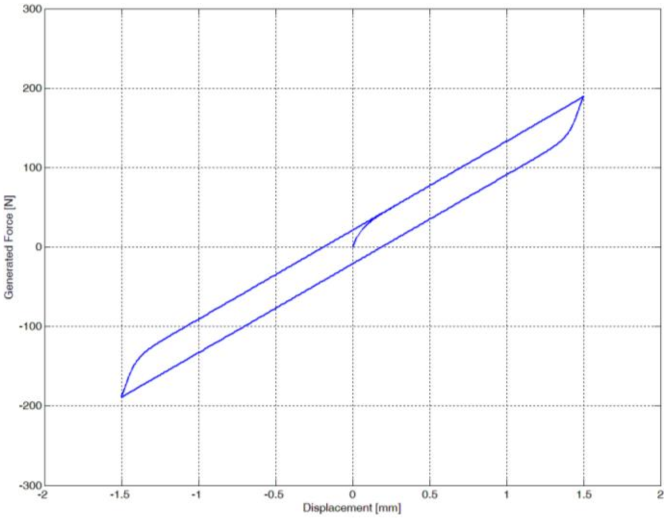

Figure 6. Simulated force-displacement loop of the friction damper under sinusoidal displacement.

VISCOELASTIC DAMPERS

Viscoelastic materials employed within viscoelastic dampers for structural seismic applications commonly comprise copolymers or glassy substances, adept at energy dissipation via shear deformation mechanisms. An illustrative model of such a damper entails a configuration wherein layers of viscoelastic material are adhesively affixed between two steel plates. In the event of seismic loading, the structural oscillations engender a relative displacement between the two steel plates and central plate, consequently facilitating energy dissipation through shear deformation, as depicted in Fig. 7.

Figure 7. Viscoelastic damper application in a building.

The viscoelastic damper noted several advantages as reducing vibration over a wide frequency range. In addition, the use of viscoelastic materials is a cost-effective technology on the market that can be incorporated during construction to improve cushioning and reduce protection costs compared to other technologies. These advantages make it preferable to other types of passive dampers. Contrariwise, viscoelastic damping works best only with certain types of vibrations, /14/.

The generated force by the damper is given by

$$f_{vf} = \gamma_0 G^* A \cdot \tag{7}$$

The maximal damper displacement is

$$\Delta_0 = \gamma_0 t \, , \tag{8}$$

where: A and t are section and thickness of viscoelastic material; G^* is shear complex module expressed by

$$G^* = \sqrt{(G')^2 + (G'')^2} \, , \tag{9}$$

$$G' = G^* \sin(\delta t) \, , \tag{10}$$

$$G'' = G^* \cos(\delta t) \cdot \tag{11}$$

Under a sinusoidal displacement with amplitude of 1.5 cm and frequency of 2.5 Hz applied to the device, the generated force function of damper displacement is illustrated in Fig. 8.

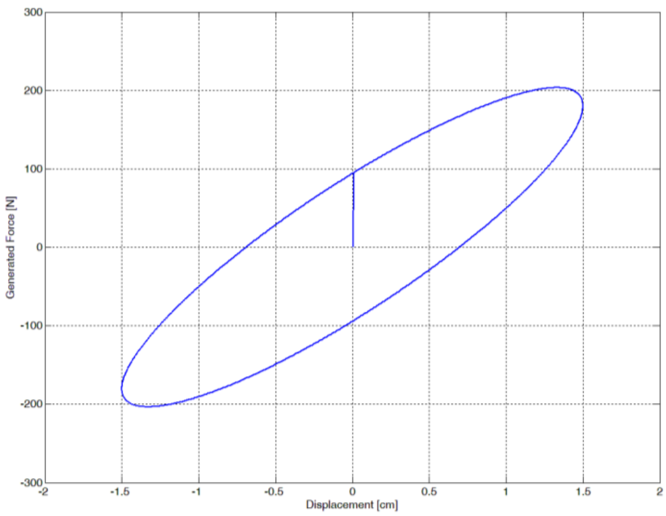

Figure 8. Simulated force-displacement loop of the visco-elastic damper under sinusoidal displacement.

VISCOUS FLUID DAMPERS

Viscous devices typically encompass viscous walls and dampers. The slimy wall, serving as a key component, manifests as a substantial plate housed within a slender steel enclosure brimming with a highly viscous medium. Illustrated in Fig. 9, the shock absorber configuration commonly comprises a piston immersed in a reservoir saturated with a silicone compound or analogous viscous oil. This reservoir may incorporate a series of minute orifices facilitating fluid flow across the piston, thereby regulating damping characteristics.

These dampers make it possible to absorb the energy by the deformation of the fluid induced by the movement of floors. The force generated by the viscous fluid damper is due to a pressure difference across the piston head, when the damper is subjected to a compressive force the volume of fluid is reduced by the product of the stroke of the piston rod. This change in fluid volume is accompanied by the development of a restoring force, /12, 13/. The generated control force of the damper is given by

$$f_{vf} = c_{vf} \dot{x}^{\alpha} \sin \dot{x} \, , \tag{12}$$

where: c_{vf} is damping constant; α is a constant depending on fluid damper; and $\dot{x}$ is cross damper velocity. Under a sinusoidal displacement with amplitude of 1.5 cm and frequency of 2.5 Hz applied to the device, the generated force function of damper displacement is illustrated in Fig. 10.

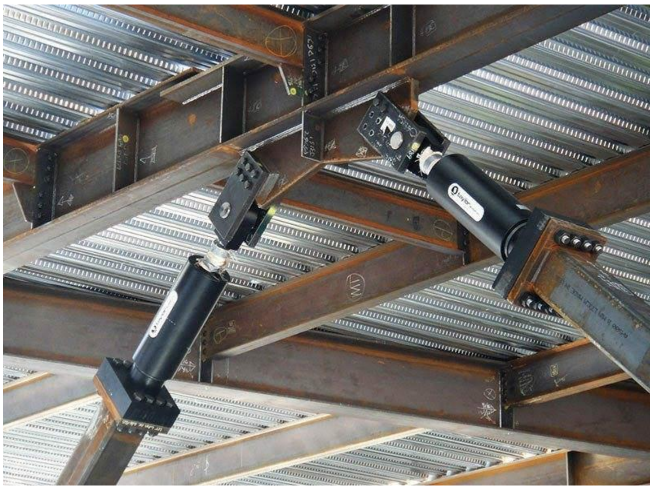

Figure 9. Viscous fluid damper application in steel farm structure.

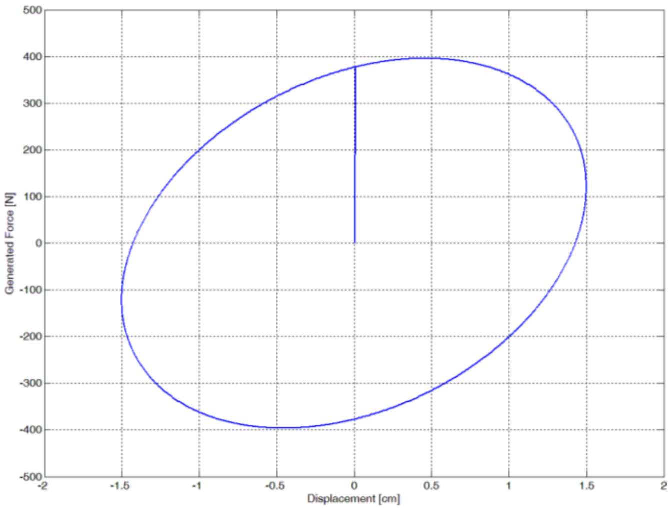

Figure 10. Simulated force-displacement loop of the viscous fluid damper under sinusoidal displacement.

NUMERICAL APPLICATION

In investigations concerning passive control methods, the utilisation of multiple scale prototypes serves to evaluate the efficacy of mitigating structural displacement under dynamic loading scenarios. The scale model under scrutiny, delineated by Zizouni et al. /15/, comprises a three-story steel frame. Dynamic loading is simulated by inducing excitation in the structure to mimic the seismic forces experienced during the 2003 Boumerdès earthquake, as detailed in Fig. 11. Control interventions are implemented using energy dissipating dampers, strategically positioned on the ground floor of the prototype structure, as depicted in Fig. 12. The salient characteristics of the tested structure are expounded upon as follows:

$$\left[M_s\right]=\begin{bmatrix}98.3 & 0 & 0\\ 0 & 98.3 & 0\\ 0 & 0 & 98.3\end{bmatrix} \text{ kg}, \quad (13)$$

$$\left[K_s\right]=\begin{bmatrix}12 & -6.84 & 0\\ -6.84 & 13.7 & -6.84\\ 0 & -6.84 & 6.84\end{bmatrix} \times 10^5 \text{ N/m}, \quad (14)$$

$$\left[C_s\right]=\begin{bmatrix}175 & -50 & 0\\ -50 & 100 & -50\\ 0 & -50 & 50\end{bmatrix} \text{ Ns/m}, \quad (15)$$

where: M_s, K_s and C_s are mass, stiffness and damping matrices of the tested structure.

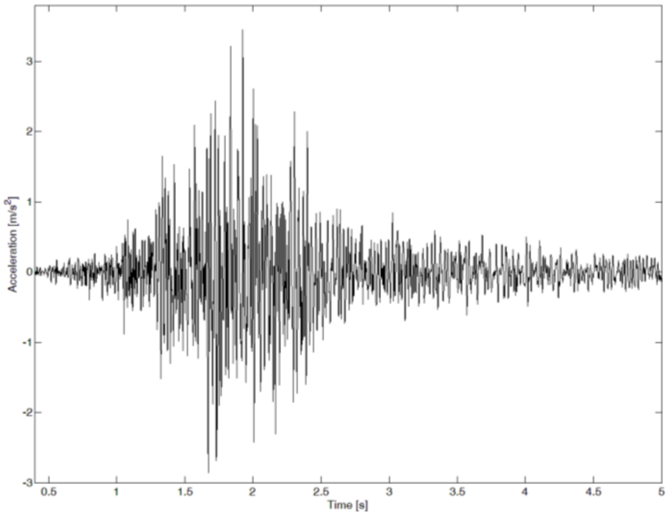

Figure 11. The North-South time-scaled 2003 Boumerdès earthquake excitation.

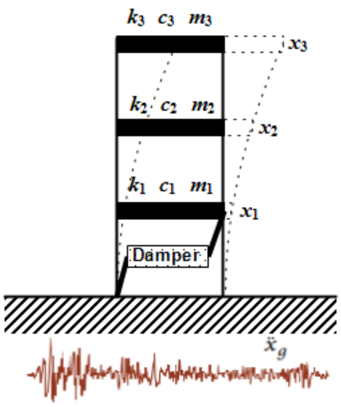

Figure 12. Schematic presentation of the tested structure controlled by dissipater energy damper.

To evaluate the effectiveness of energy dissipater dampers in controlling structural vibration, the peak displacement ratio criterion is calculated as

$$P_{dr}=\frac{\bar{x}_i-x_i}{\bar{x}_i}, \quad (16)$$

where: P_{dr} is peak displacement reduction, $\bar{x}_i$ is maximum displacement of the i^{th} uncontrolled floor; and x_i is maximum displacement of the i^{th} controlled floor. The peak displacement reductions using each damper are listed in Table 1.

As illustrated in Table 1, the employed dampers exhibit noteworthy displacement performance during the seismic event of 2003. Particularly, the metallic yield damper demonstrates a significant 10.78 % reduction in displacement at the structure's third floor, showcasing its efficacy as a passive damping mechanism. In contrast, the friction or viscoelastic damper achieves a peak reduction of 12 % on the same floor. Notably, the employment of a viscous fluid damper yields the highest peak displacement reduction at 14.65 %. These simulation outcomes are graphically depicted in Fig. 13, providing a visual representation of the observed trends.

Table 1. Floor peak displacement reduction under the 2003 earthquake.

Floors	Displacement reduction ration (%)			
	metallic yield damper	friction damper	viscoelastic damper	viscous fluid damper
1	14.66	18.44	19.88	20.66
2	11.45	15.21	14.39	15.19
3	10.78	12.12	12.65	14.65

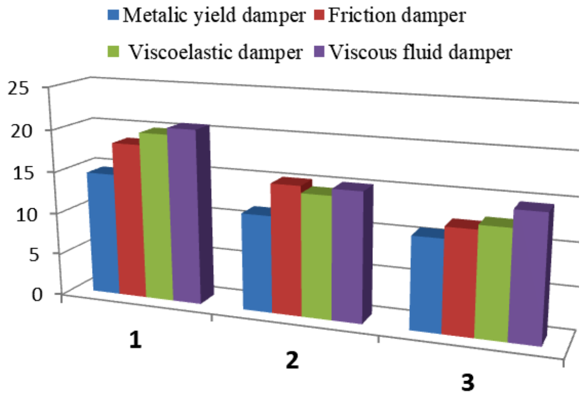

Figure 13. Histogram of the peak displacement reduction simulation results using each damper.

The histogram depicted in Fig. 13 demonstrates a high degree of uniformity in the control outcomes of the energy dissipater dampers. Across each floor, the computed peak displacement reduction during the 2003 Boumerdès earthquake consistently exceeds 10 %. Remarkably, the proposed control strategy operates effectively without reliance on automation, intricacy, or external energy sources, thereby presenting a viable solution for safeguarding structures subjected to seismic excitations.

CONCLUSION

As expounded upon in the extensive review presented within this manuscript, prominent dissipative energy devices assume a critical role across diverse structural paradigms, functioning to mitigate vibrations and ensure human safety. The effectiveness of each of these devices is emphasised by their potential for seamless integration within vibrational systems. Simulation results robustly validate the feasibility of each highlighted control device for deployment in structural vibration mitigation. Particularly noteworthy are the discernible benefits of these devices, evidenced by their capability to achieve reductions exceeding 10 % in peak displacement on the most dynamically active floor. Furthermore, this scholarly discourse unveils, through rigorous numerical analysis, one of the predominant methods of employing passive control devices, thereby contributing significantly to the expanding corpus of knowledge in this specialised field.

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