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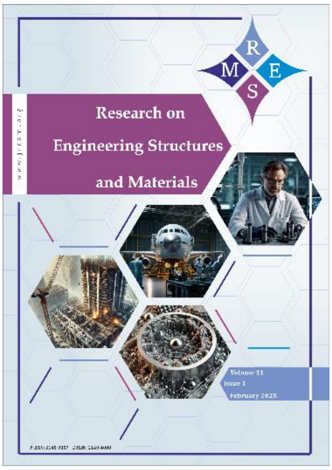

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Research Article

Comparison of single and multi-coil self-powered MR damper subjected to cyclic and earthquake loading for structural vibration control

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Abstract

A promising solution for semi-active vibration control of different dynamic systems is to use magnetorheological (MR) dampers. In the present study, the investigation focuses on developing a novel single and multi-coil self-powered magnetorheological (MR) damper system using electromagnetic induction (EMI) for seismic mitigation. The conventional MR dampers, which rely on external power sources, can be unreliable and impractical in earthquake-prone locations. Thus, the EMI device connected to the MR damper can be used as an effective and alternative power source for the MR damper, results in a self-powered system. The proposed energy-harvesting system is an MR damper placed above the top of the piston. The coil is wound around the piston, and the outer casing with a ferrite magnet is fixed. As the mechanical energy of the piston is converted into electrical energy, its self-tuning capacity is a perfect fit for structural vibration control applications. The MR damper is subjected to cyclic and time-history loading. At a maximum amplitude of 15 mm, the damper generated 1767.8 N for cyclic loading and -1780 N for earthquake loading, the El Centro earthquake 1940 is considered for the study. By placing EMI, the mechanical energy is converted into electrical energy and powers the damper to avoid external power. The experimental results showcase enhanced damping forces and adaptability, thereby establishing it as an innovative and effective it can be alternative to conventional MR dampers for vibration control in future.

1. Introduction

Indeed, the progress in earthquake engineering has led to the development of control systems for structures and infrastructure, focusing on monitoring and minimizing the impact of seismic vibrations. A key technological innovation is the use of self-powered Magnetorheological (MR) dampers, which can convert vibrating energy into electrical energy, making them highly favored semi-active damping devices. Li et al. [1] explored the development of self-powered MR dampers aimed at enhancing reliability and reducing costs in remote locations by converting vibration energy into electricity. Bui et al. [2] designed a washing machine damper utilizing magnets to convert machine vibrations into electricity, effectively minimizing vibration, while investigating electromagnetic parameters and energy conversion efficiency in vehicle suspension systems. Gao et al. [3] developed self-powered MR dampers, showcasing their potential in reducing installation space and costs. Hu et al. [4] introduced MR dampers with self-powered capabilities, eliminating size, cost, and energy consumption concerns. Taking it a step further, Hu et al. [5] combined energy harvesting with automatic vibration detection, providing an innovative solution. Wang et al. [6] introduced methods for tackling cable vibration.

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Jamshidi et al. [7] presented a self-powered MR damper that generates electricity from movement, significantly reducing vibration. Dyke et al. [8] explored an adaptive damper harvesting vibration energy for more autonomous and efficient structures, integrating vibration sensors and a small power source to automatically adjust building dampers. Chen et al. [9] proposed an MR damper combining energy harvesting, sensing, and damping, making it smaller, cheaper, and self-powered for various applications. Zhu et al. [10] replaced conventional dampers with energy-harvesting linear electromagnetic dampers for vibration mitigation, emphasizing their effectiveness in energy storage and performance. Wang et al. [11] advocate for the substitution of conventional dampers with energy-harvesting linear electromagnetic dampers, highlighting their dual advantages of dissipation and power generation. Wang et al. [12] developed a self-sensing MR damper with improved control and sensing capabilities for cost-effective and intelligent vibration control applications. Choi et al. [13] discussed the self-powered MR damper utilizing vibration energy to enhance vibration isolation in structures. Lam et al. [14] investigated the MR damper with built-in sensors for real-time control of building vibrations. Lai et al. [15] integrated an IRDS sensor into commercial dampers, optimizing their performance for self-sensing purposes in advanced vibration control applications. Chen et al. [16] developed a self-powered MR damper integrating energy harvesting, sensing, and damping for benefits such as lower cost, smaller size, and higher reliability. Choi et al. [17] developed an energy-harvesting vibration control system based on an electromagnetic device, demonstrating its efficiency in reducing structural responses. Sapinski et al. [18] introduced a self-energized MR damper with an internal vibration power generator, eliminating the need for external power sources for vibration control. Chen et al. [19] demonstrated a self-energized MR damper with multifaceted design potential, offering significant benefits in areas such as robotics, prosthetics, and vehicle suspension. Cruze et al. [20] evaluated six MR fluids, incorporating different carrier liquids and carbonyl-iron (CI) particle ratios, for their rheological performance. Notably, MRF 80 outperformed the retail MRF 132 DG in damping, showcasing a peak force of 0.536 kN in cyclic load tests with a 1-mm annular gap. This suggests its potential for applications requiring precise and adaptable damping forces across diverse fields. Utami et al. [21] evaluated the performance variation of MR fluid under extended cyclic stress. The investigation revealed a substantial increase in the damping force of the MR damper, both in on and off modes, growing by 44% for the on-state condition and 90% for the off-state condition after 170,000 operational cycles. Changes in magnetic particle sizes and shapes within the MR fluid were attributed to an inadequate grasp of technology (IUT) and a viscosity decrease due to oxidation during extended operation. Wang et al. [22] explored the impact mitigation potential of magnetorheological fluids (MRFs) under magnetic fields using rheological analysis with a speed-controlled capillary magneto rheometer. The study demonstrated consistent shear-thinning behavior and correlated viscosity uniformity across various excitation levels with the strength of the magnetic field, enhancing the technical application of MRFs in impact mitigation. Daniel et al. [23] conducted a study on the sedimentation rates of grease, lubricant oil, and silicone oil as three base fluids for MR fluids. Results indicated that MR fluid with silicone oil exhibited the lowest sedimentation rate, emphasizing the crucial role of base fluid selection in maximizing MR fluid performance for real-world applications. Xu et al. [24] conducted a study comparing three control strategies for MR damper-equipped building structures: bi-state, modified bi-state, and intelligent control. The results indicated that while bi-state control might lead to parameter overruns, the modified strategy mitigated this issue. Intelligent control, which integrated neural network prediction, effectively reduced earthquake responses, emphasizing the efficacy of intelligent strategies for optimal MR damper performance in reducing dynamic responses. Xu et al. [25] developed a novel real-time control approach using MR dampers for earthquake mitigation in structures. They established the Bingham model for MR dampers and demonstrated their efficacy in reducing seismic responses through numerical analysis. Results showed that the proposed real-time control method outperformed traditional approaches. It was aided by the highly efficient Levenberg-Marquardt algorithm for training the control neural network, highlighting the effectiveness of MR dampers and innovative real-time control strategies in earthquake hazard mitigation. Yang et al. [26] investigated the dynamic characteristics of three-coil MR dampers, revealing full hysteresis curves and significant energy dissipation capacity, with damping force saturation beyond 1.2 A excitation current. Energizing all coils enhanced damping force amplitude and saturation, while the proposed modified micromodels accurately simulated force-velocity hysteresis curves and magnetic saturation. These findings offer insights for optimizing control strategies and enhancing the seismic performance of structures with multicoil MR dampers. Yang et al. [27] explored a micro-macro mathematical model incorporating MR fluid microstructure parameters into classic models. This model accurately described the MR damper's dynamic properties. Validation confirmed efficacy, while numerical analysis highlighted nonlinear hysteretic behavior, providing insights for optimizing MR fluid formulations and enhancing damper efficiency. Daniel et al. [28] studied the importance of building safer structures in response to earthquake-related losses and explored MR dampers as a potential solution. Experimental investigations on a scaled-down RC frame with a single piston shear mode MR damper demonstrated a 40–50% reduction in displacement and a 45–60% increase in energy dissipation capacity. The study highlighted the effectiveness of MR dampers in enhancing vibration reduction, with analytical and experimental results confirming their efficiency and potential for seismic resilience in civil engineering applications. Cruze et al. [29] developed a novel approach to MR damper design, emphasizing its semi-active vibration control capabilities. They conducted experimental and numerical investigations on a new MR damper design featuring multi-coils for enhanced shear force production. Results demonstrated significant displacement reduction and increased damping force under seismic events, highlighting its effectiveness in improving seismic resilience. The proposed device showcased superior performance over conventional control devices, offering a promising solution for seismic mitigation in earthquake-prone areas. Hu et al. [30] investigates the performance of a self-powered, multi-coil MR damper under simulated seismic excitation. It employs simulations to analyze the damper's response to various earthquake loading scenarios. The findings highlight the effectiveness of the multi-coil design, demonstrating how the coil configuration and control strategies can be optimized to achieve superior damping performance, potentially offering a significant advantage in mitigating the impact of earthquakes on structures. Kariganaur et al. [31] presents a comparative study on the effects of single-coil and multi-coil magnetorheological (MR) dampers using finite element analysis. The study finds that multi-coil MR dampers offer superior performance in controlling vibrations compared to single-coil dampers. The results suggest significant potential for multi-coil designs in enhancing the stability and safety of structures subjected to dynamic loads.

In the proposed research, the comparison of a single and multi-coil self-powered MR damper subjected to cyclic and earthquake loading is investigated. The main focus of this study is to conduct a comprehensive analysis of single and multi-coil MR dampers. It begins with the 3D modelling of self-powered MR dampers using AutoCAD. Then, the models are fabricated using mild steel. After the fabrication process, the MR dampers are assembled, the piston coils are wound with copper coils, and the EMI systems are placed at the top of the piston. Then, MR fluid is filled inside the cylinder. The MR dampers are tested by cyclic loading at three different displacement levels of 5, 10, and 15 mm. For time history loading, El Centro has been considered for the study.

2. Self-Powered MR Dampers

In general, supplying of current is required to activate the electromagnetic coils in an MR damper. There are several ways for a self-powered MR damper to convert mechanical energy into electrical energy in the event of high-magnitude earthquake. However, the amount of electrical energy produced is enough to create the damping force needed to keep the buildings from vibrating during a seismic event. Thus, self-power mechanisms are essential for civil engineering applications, particularly for seismic resistant buildings.

3. MR Fluid

A blend of magnetic particles and oil makes up MR Fluid, a smart liquid. The particles in the liquid align themselves when exposed to a magnetic field, changing the liquid's viscosity, yield stress, and magnetic susceptibility. The fluid's high receptivity makes precise control possible. Through testing, the most efficient mixture was found to be carbonyl iron and synthetic oil without the inclusion of surfactants. The carbonyl iron's spherical form facilitates good suspension in the fluid, and its high saturation magnetization adds to its potency. To synthesize the fluid, carbonyl iron of grade R is mixed with the carrier fluid and stirred for 8 hours at room temperature. The final mixture contains 50% carbonyl iron and 50% carrier fluid. This proposed MRF 50 shows a maximum yield stress of about 93.34 kPa and a viscosity of 0.28 Pa s. [20]. Fig. 1

Fig. 1. Magnetorheological fluid

4. Electromagnetic Induction System

Electromagnetic induction (EMI) is the production of an electromotive force (EMF) across an electrical conductor in a changing magnetic field. It can also be described as the creation of current by moving an electric conductor through a static magnetic field. MR dampers incorporate EMI systems for self-power. MR dampers have EMI components that include a permanent magnet and a copper coil. As movement occurs, kinetic energy converts into electrical energy, resulting in changes in the damping capabilities of the device. Fig. 2.

Fig. 2. Electromagnetic induction system

5. Self-Powered Single Coil MR Damper

The configuration of the MR damper was designed and fabricated using mild steel material. The external structure includes a hollow cylinder, MR fluid, magnet, and magnet casing components, as depicted in Fig. 3. The proposed self-powered single-coil MR damper consists of a single-coil piston rod wound with a standard wire gauge (SWG) 22 copper coil 0.8 μ. The damper consists of a cylindrical casing with an external diameter of 60 mm and an internal diameter of 50 mm, with a depth of 280 mm. The piston has a diameter of 25 mm and a length of 130 mm, wound with a copper coil, which has a 0.8 mm diameter with 1462 coil turns [28], as shown in Fig. 4.

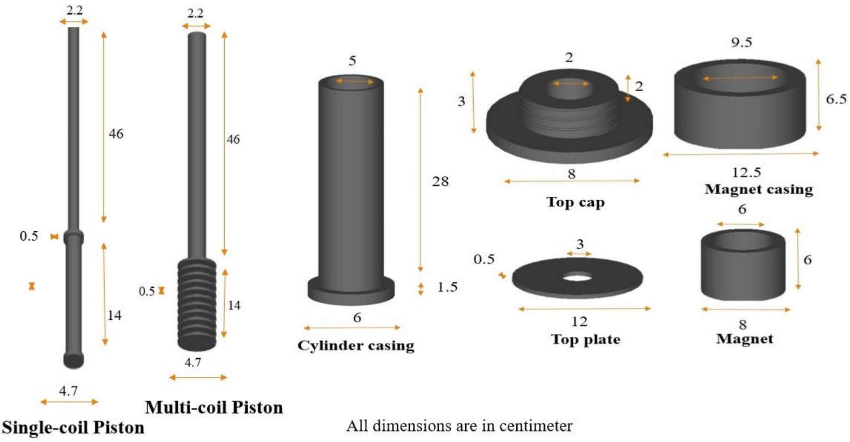

Fig. 3. Dimensions detailing of self-power single and multi-coil MR Damper

A self-powered magnet casing is placed at the top, measuring 60 mm in height and 80 mm in diameter at the center. Ferrite magnet grade N 42 is used for the study to create a self-powered MR damper. A ferrite magnet is placed to produce self-powered energy to activate the MR damper. In the self-powered single-coil piston head, 326 turns of coil were wound with a copper coil of 0.8 μ parallel to the magnet to generate EMI. The annular gap of 1 mm is maintained for the flow of MR fluid. The EMI system is placed above the cylinder cap. During operation, the piston rod moves in response to external movement, allowing the

MR fluid to flow throughout the annular gap of the cylinder. When the copper coil is magnetized using a self-powered system, the rheology of the MR fluid within the flow channel generates shear stress, impeding the relative motion of the piston head.

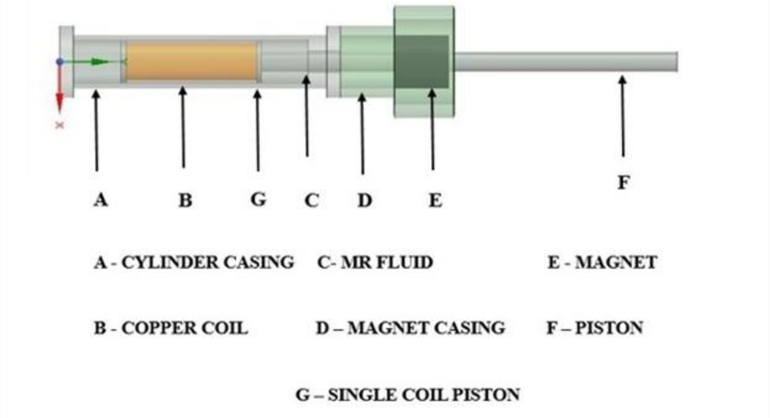

Fig. 4. 3D model self-power single-coil MR Damper

6. Self-powered Multi Coil MR Damper

The fluid flow through two adjacent cores in the piston is strengthened by the alternating polarities in the magnetic field, which benefits from utilizing the toothing system in the piston configuration. In contrast, 11 piston poles and 10 coils with a uniform distance of 5 mm and a depth of 10 mm were constructed in the proposed MR damper to increase the amount of shear force [29]. Shear forces on the piston's sides increase as the number of flow gaps increases with the number of piston poles, as shown in Fig. 5. The suggested self-powered MR damper has the capacity to produce a maximum damping force of 1.7 kN. The design indicates that an electromagnetic circuit can generate more flux lines in the flow gaps in milliseconds to produce 1.7 kN of damping force. The fluid is strengthened through two adjacent cores when the toothing system is used in the piston configuration because of the magnetic field's alternating polarities within the piston.

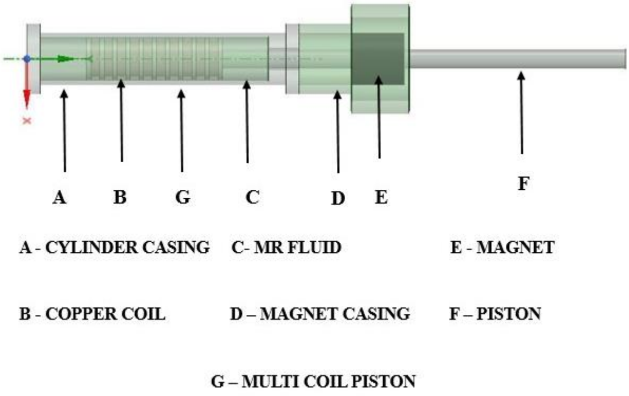

Fig. 5. 3D model self-power Multi-coil MR Damper

7. Working Principle

A new self-powered MR damper operates based on a mechanical mechanism. Figs. 4 and 5 depict a 3D model of the self-powered MR damper. The device comprises a piston, top cap, MR fluid, SWG 22 copper coil, magnet, and magnet casing. Vibration energy is converted into electrical energy to power the self-powered MR damper, thus eliminating the need for external electrical energy. During operation, the piston rod moves vertically, and a coil wound around the top of the piston cap, parallel to the magnet, generates electromagnetic induction (EMI) by producing electromagnetic force due to changes in the magnetic field. Therefore, the self-powered MR damper can perform adaptive damping adjustment without any external power supply equipment, reducing the impact of various exterior disturbances on the device's performance and improving its practicality and reliability. The main dimensional parameters of the proposed self-powered MR damper are tabulated in Table 1.

Table 1. Dimensional detailing of the proposed self-powered MR damper

Parameters	Single coil MR damper	Multi coil MR damper
Cylinder casing	295 mm	295 mm
Diameter of copper coil	0.8 mm	0.8 mm
No. of turns (copper coil)	1462 turns	122 turns for each pole
MR fluid (ratio)	50:50	50:50
Piston length	600 mm	600 mm
No. of. piston pole	-	10 nos
Magnet	Ferrite magnet grade N 42	Ferrite magnet grade N 42
Magnet size	80 mmx60 mm	80 mmx60 mm
Magnet casing	125 mmx65 mm	125 mmx65 mm
Coil turns at top	326 turns	326 turns

8. Experimental Investigation on Self-Powered MR Damper

The performance of the MR damper can be determined by subjecting it to cyclic loading in the MTS Universal Testing Machine (UTM) at the Structural Engineering Laboratory of Karunya Institute of Technology and Science, Coimbatore.

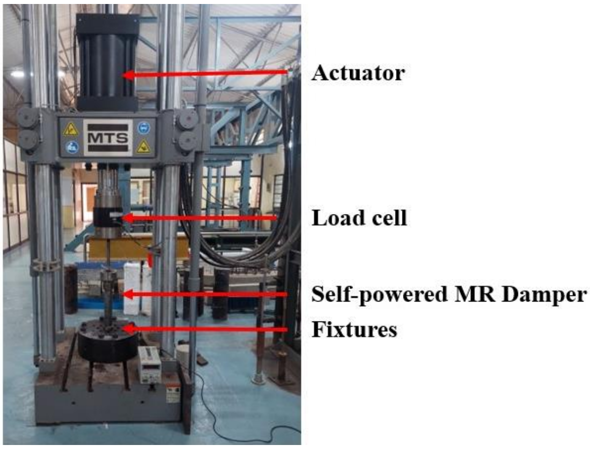

Fig. 6. Testing of self-Powered MR damper

The single and multi-coil self-powered MR dampers were tested at various displacements ranging from 5 mm to 15 mm. The experimental setup for the cyclic loading test on a single- and multi-coil self-powered MR damper is presented in Fig. 6. The setup includes a load cell, a base plate or fixtures, and a hydraulic actuator. The piston base is fixed to the UTM base plate using a fixture, while the piston rod is attached to the load cell. The input to the UTM is controlled by a computer-regulated hydraulic actuator.

9. Cyclic Loading

Cyclic loading on a self-powered MR damper involves subjecting it to repeated force or displacement cycles to assess its durability and performance under real-world conditions. At a frequency of 0.2 Hz for 10 repetition cycles, the displacement values of 5, 10, and 15 are used to determine the maximum force exerted by the self-powered MR damper. The experimental results of damping force are plotted in Figs. 7, 8, and 9. The results are tabulated in Table 2.

Table 2. Difference between single and multi-coil self-sensing MR damper on cyclic loading

Single Coil Self-Sensing Mr Damper		Multi Coil Self-Sensing Mr Damper	
Displacement	Load	Displacement	Load
5mm	1256.4 N	5mm	1350.8 N
10mm	1392.6 N	10mm	1570.8 N
15mm	1566.8 N	15mm	1767.8 N

The observed results for the single-coil self-powered MR damper indicate a maximum damping force of 1256.4 N at a 5mm displacement, 1392.6 N at a 10 mm displacement, and 1566.89 N at a 15 mm displacement. Multi-coil MR dampers typically exhibit higher damping forces compared to single-coil dampers due to the presence of multiple coils generating magnetic fields. Additionally, multi-coil dampers are capable of generating higher shear forces in the MR fluid compared to single-coil MR dampers.

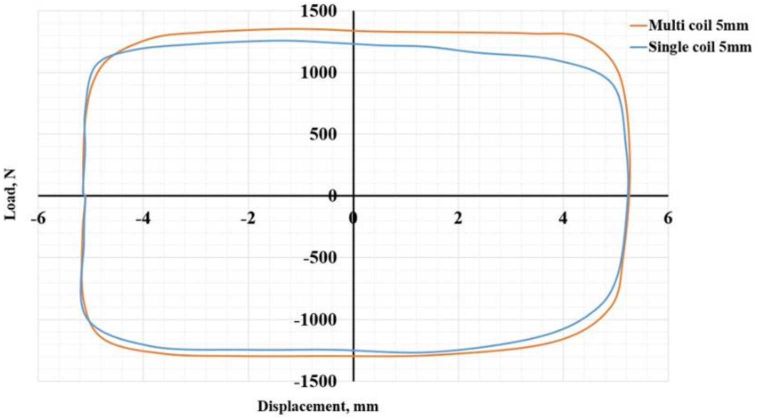

Fig. 7. Force and Displacement graph for single and multi-coil Self-power MR Damper for 5 mm displacement

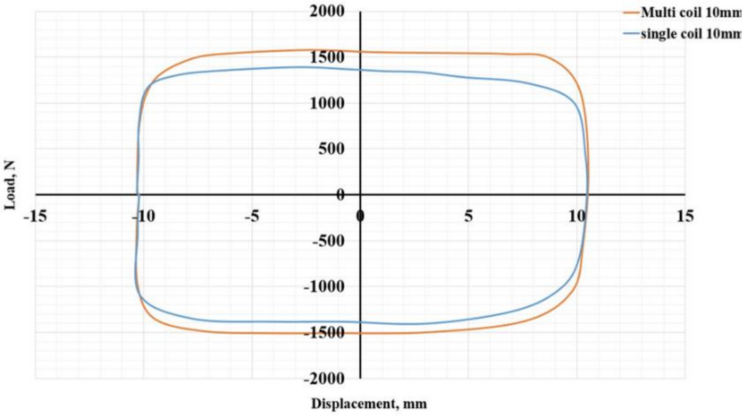

Fig. 8. Force and Displacement graph for single and multi-coil Self-power MR Damper for 10 mm displacement

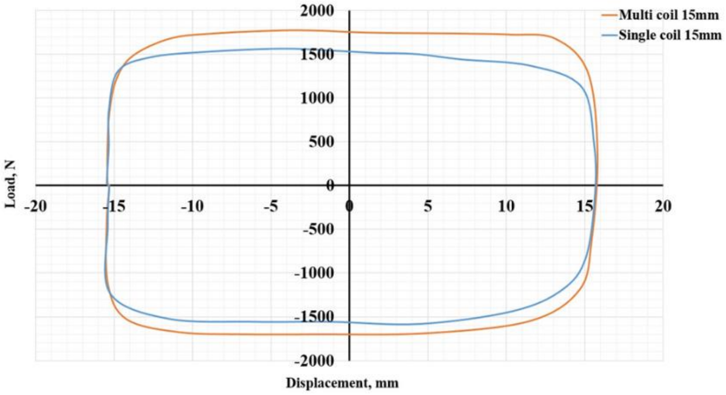

Fig. 9. Force and Displacement graph for single and multi-coil Self-power MR Damper for 15 mm displacement

10. Earthquake Loading

Earthquake loading on self-powered MR dampers involves adaptation to dynamic forces. These dampers utilize MR fluids, offering real-time adjustments in viscosity and mitigating structural vibrations during seismic events. In this study, the El Centro earthquake of 1940 was a significant seismic event in California, USA.

Table 3. Difference between single and multi-coil self-sensing MR damper on earthquake loading

El-Centro 1940 Earthquake Loading	
Self-Powered Single-Coil MR Damper	-1259.7 N
Self-Powered Multi-Coil MR Damper	-1780.0 N

Fig. 10 shows the time history loading ground acceleration converted to displacement and employed to simulate the response of self-powered MR dampers. The objective is to determine the earthquake loading capacity of both single and multi-coil MR dampers. The experimental results of earthquake loading are plotted in Fig. 11, and the results are tabulated in Table 3.

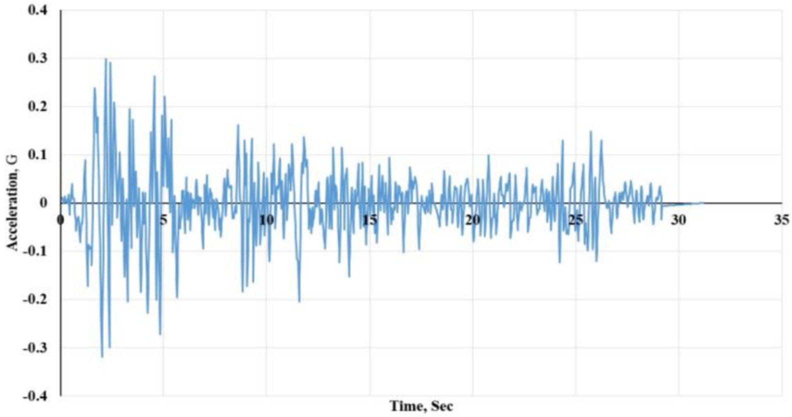

Fig. 10. Time history of El Centro earthquake, 1940

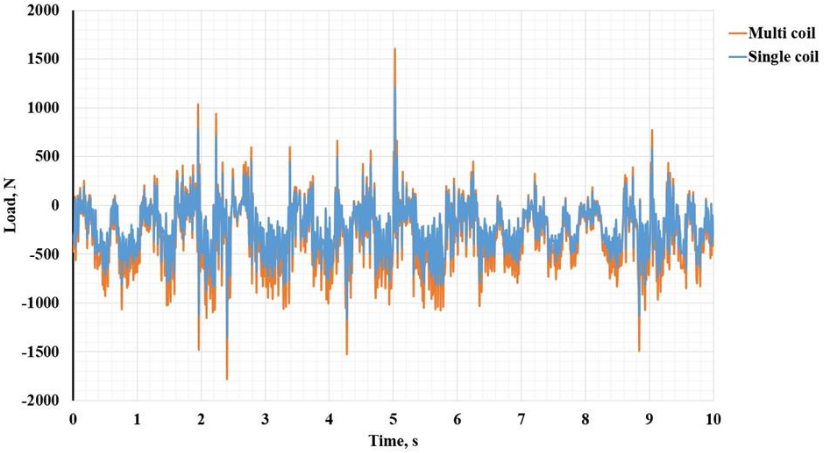

Fig. 11. Earthquake loading of single and multi-coil Self-power MR Damper

11. Conclusion

In this study, a novel functional-integration MR damper was designed, fabricated, and tested. The results indicate that the proposed self-powered single-coil MR damper exhibits a damping force of 1566.8 N at a 15 mm displacement, while the self-powered multi-coil MR damper demonstrates a damping force of 1767.8 N under cyclic loading; this represents a 12.8% increase in damping force compared to the single-coil self-powered MR damper. For earthquake loads, the single-coil self-powered MR damper shows a damping force of -1289.7 N, whereas the multi-coil self-powered MR damper has a compression value of -1780 N in seismic conditions; the multi-coil self-powered MR damper displays a 34.2% increase in damping force compared to the single-coil self-powered MR damper. The stiffness of a single-coil MR damper is 104.45, while the stiffness of a multi-coil MR damper is 117.8. Compared to the single-coil MR damper, the multi-coil MR damper has greater stiffness, representing a 12.7% increase in stiffness. Additionally, the multi-coil MR damper has a 16% reduction in the volume of MR fluid compared to the single-coil MR damper, which has a volume of 409.76 ml. In conclusion, the experimental investigation demonstrates that the proposed self-powered multi-coil MR damper device has better performance compared to a single-coil MR damper because a multi-coil piston produces more magnetic field compared to a single-coil piston. This is due to the presence of piston poles in the multi-coil design. Additionally, the volume of MR fluid is lower in the multi-coil piston compared to the single-coil piston. Therefore, it can be considered an innovative and effective alternative for enhancing a building's seismic durability in seismically active areas in the future, effectively protecting structures from seismic resistance issues. In the future, the damper will be placed diagonally in the RC frame, and the performance of the damper will be studied when the frame is subjected to cyclic loading and real-time earthquake loading.

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