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A Review on Mechanical Motion Rectifier for Energy Harvesting

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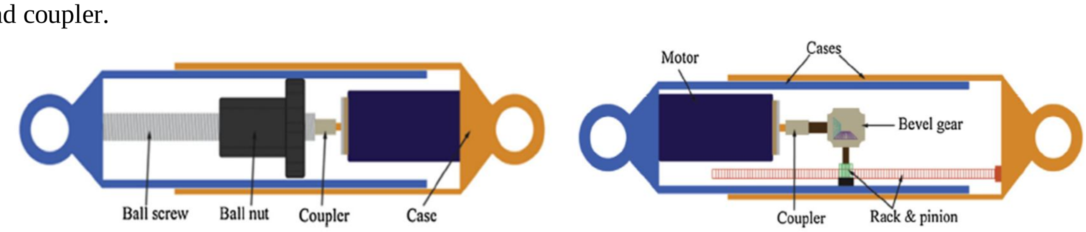
Abstract: The conventional vehicle suspension dissipates the mechanical vibration energy in the form of heat which waste considerable energy. The regenerative suspensions have attracted much attention in recent years for the improvement of vibration attenuating performance as well as the reduction of energy dissipation. In fact, the vibrations in some situations can be very large, for example, the vibrations of tall buildings, long vehicle systems, railroads and ocean waves. With the global concern on energy and environmental issues, energy harvesting from large-scale vibrations is more attractive. This paper introduces the existing research and significance of regenerative shock absorbers and reviews the potential of automotive vibration energy recovery techniques; then, it classifies and summarizes the general classifications of regenerative shock absorbers.
Keywords: Mechanical vibration, regenerative suspension, energy dissipation, railroads, ocean waves, vehicle.

I. INTRODUCTION

The generalizability of the mechanical-based harvesting system observations presented in this section is subject to certain constraints; therefore, the mechanical-based system has a larger conversion capacity than others. For example, increasing the possibility of system failure, notably in automobile suspension due to repetitive vibration shocks as a result of solid mechanical elements than a hydraulic-based system that accumulates the input shocks through the hydraulic loop [1]. Despite its simplicity and efficacy, another disadvantage of mechanical-based systems is the lack of controllability of mechanical elements in active or semi-active systems. There is plenty of space for advancement in identifying potential solutions to these limitations, such as developing mechanical transmission-based electromagnetic rotatory energy harvesting absorbers with improved durability, compactness, and dynamics [2]. The kinetic energy represented by the perpendicular vibration of the vehicles suspension is harvested to electrical energy employing a rotary electromagnetic generator in electromagnetic rotary harvesters. To drive the rotary motor, the perpendicular vibration is converted into a rotating motion by a transmission mechanism. Several linear to rotary motion transmissions have been prototyped and developed utilizing different mechanisms and designs based on electromagnetic rotary harvesters. Mechanical transmission-based electromagnetic rotary harvesters and hydraulic transmission-based electromagnetic rotary harvesters are the two most frequent linear-to-rotary motion transmissions, as per the literature. Transmission with a mechanical basis Because of its easy construction and high conversion efficiency, rotary harvesters may be one of the most prevalent designs among numerous energy collecting structures. Various regenerative suspension techniques based on a mechanical idea have been developed, prototyped, and thoroughly investigated. There are numerous types of energy regenerative suspensions based on mechanical styles such as ball-screw mechanisms [3], rack-pinion mechanisms [4], algebraic screw mechanisms [5], pullies-cables assemblies, and other mechanically based systems [6]. According to Graves et al. [7], rotary electromagnetic dampers have the potential for mechanical amplification of damping and regeneration owing to the transmission gear ratio. Whereas the transmission mechanism's rotational inertia hampered the suspension system, a remedy was offered by inserting extra dynamic components in series with the rotating damper. The structural design of the rack and pinion assembly and ball screw mechanism as a harvesting shock absorber is shown in Fig. 1. As shown in Fig. 1a, the linear vibration caused by the vehicle rolling on an uneven road is converted into a rotating motion by a rack-pinion assembly and then communicated to the generating motor via a tiny differential with two perpendicular bevel gears. In Fig. 1b, the motor's input torque is generated by a ball-screw combined with a small ball nut and coupler.



(a) (b)

Fig. 1. (a) Rack-pinion energy regeneration mechanism, (b) Ball-screw energy regeneration mechanism.

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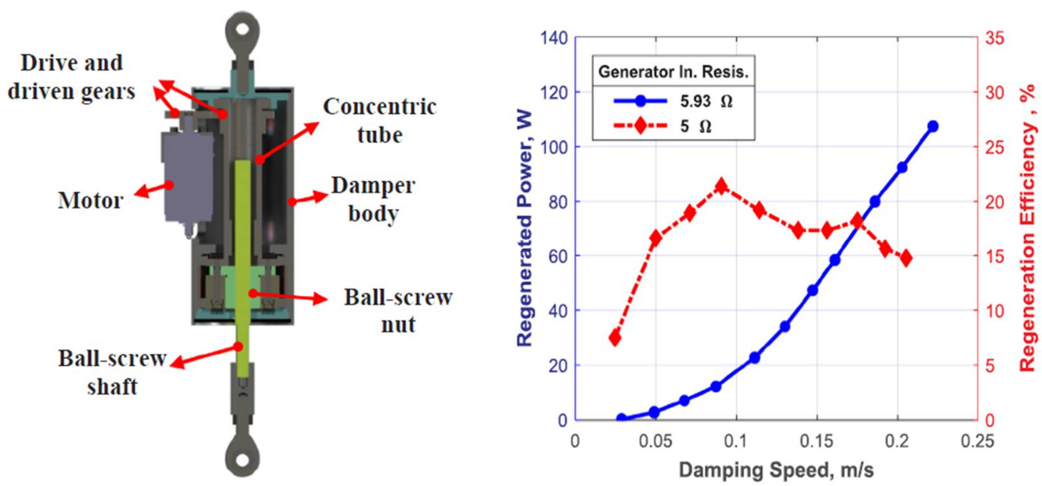
II. MECHANICAL TRANSMISSION BASED ELECTROMAGNETIC ROTARY HARVESTING SHOCK ABSORBERS

Zhang et al. [8] developed a regenerative damper prototype based on a ball-screw mechanism, which they tested experimentally on a complete car using a Road-Lab four post rig with sinusoidal stimulation at 3 and 11 Hz frequency and 5 and 10mm amplitude. The proposed prototype generated a total of 12W of collected electricity per damper. Because of the high induced inertia moment of the ball screw at high frequencies bandwidth, the proposed damper had a bad ride response when considering high frequencies excitation, but a good ride performance when considering low frequencies excitation. Song et al. [9] patented a shock absorber harvester with ball-screw mechanisms that obtained a significant power conversion density, but poor ride comfort was discovered at high frequencies bandwidth over 7 Hz. In [10], a ball-screw assembly was prototyped in a regenerative damper, and the energy harvesting performance is shown in Fig. 2a. Fig. 2b shows that an electrical regenerated power of 107W was recorded during the rebound scenario at a damping speed of 0.22ms-1 and a generator internal resistance of 5.93Ω. With a damping speed of 0.09 ms-1 and an internal resistance of 5Ω, the generation efficiency achieved around 21.3 percent.



(a) (b)

Fig. 2. Regenerative shock absorber with ball screw shaft; (a) CAD model sectional view with major components; (b) power generation performance for the proposed prototype during rebound stage.

Xie et al. [11] proposed an energy harvesting absorber with ball-screw transmissions and multiple controlled generators (Fig. 3) to collect kinetic energy lost during damping and constantly change the damping coefficient based on road conditions. At a displacement input of 3 Hz frequency and 20mm amplitude, the suggested harvester gathered an average electrical output of 32W.

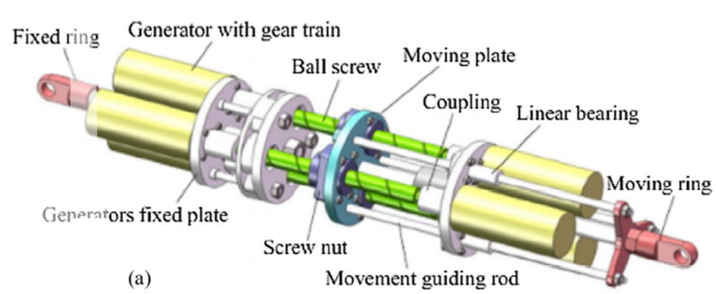
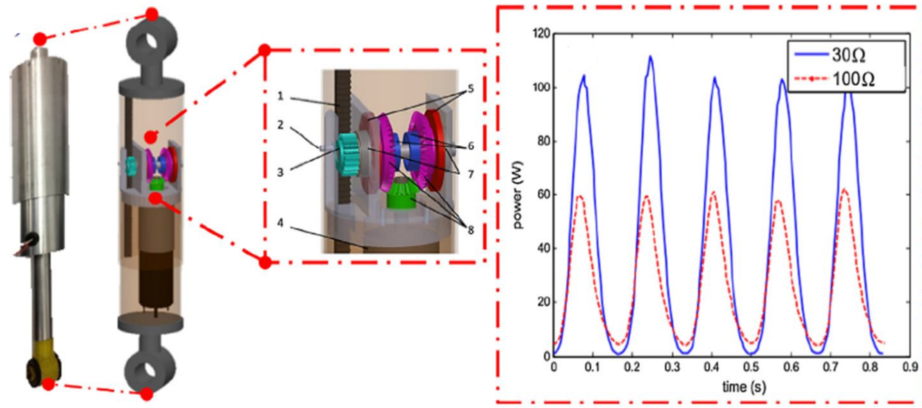


Fig. 3. Diagram of Ball-screw transmission-based energy-harvesting damper

In 2010, Zuo at al. [12] patented a prototype of a harvesting damper considering rack and pinion assembly that had a high energy density. Li et al. [13] performed both laboratory testing analysis and actual road field test for a novel design of a retrofit rack-pinion harvester which obtained a total power conversion efficiency of around 56 percent for an excitation of 30mm amplitude and 0.5 Hz vibration rate. Furthermore, when travelling at a speed of around 48 km/h on a smooth actual road, one energy-harvesting device may recover an average power of 19.2W.

In order to improve power conversion efficiency at high frequencies, bandwidth, Li et al. [14] developed a mechanical motion rectifier coupled with a rack-pinion damper (Fig. 4) to convert irregular bi-directional motion to unidirectional rotating motion with low impact pressures generated by backlash, therefore increasing conversion efficiency by lowering friction effectiveness.

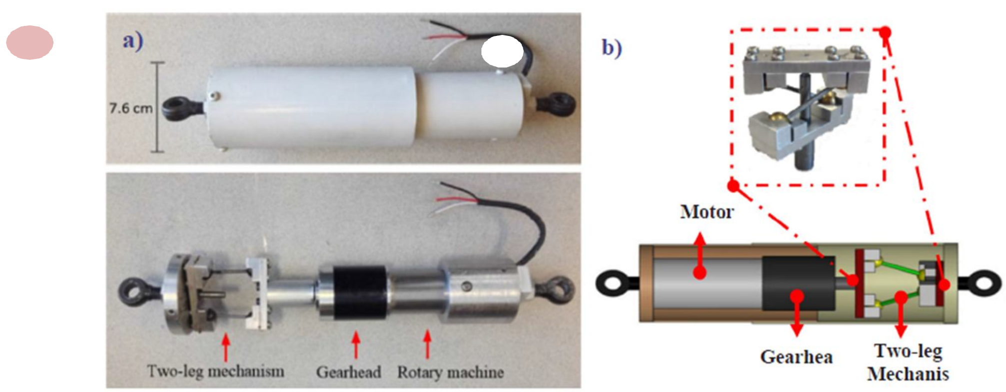


(a) (b)

Fig. 4. Regenerative shock absorber based on rack and pinion mechanism with MMR; (a) 3D model and actual prototype; (b) power generation performance at 3 Hz input frequency and 5mm amplitude.

Zhang et al. [15] designed a portable track vibration-based energy harvesting device based on a mechanical transmission of rack-pinion motion converter in which the motion is rectified using one-way bearings in response to the demand for alternative railway power sources. Based on experimental fulfilment for a vibration stimulation with a frequency of 2 Hz and an amplitude of 6 mm, a significant efficiency of around 55.5 percent was estimated.

Maravandi and Moallem [16] proposed another regeneration energy damper based on a mechanical idea (Fig. 5), which relied on a two-leg mechanism to transform vertical vibration motion into rotational motion. The prototype of the two-leg based regenerative damper recovered energy with an average mechanical efficiency of 78%. However, it is difficult to employ this kind effectively in car suspension since it was designed with the goal of power harvesting in such a manner that it overwhelms the damping properties.



(a) (b)

Fig. 5. Regenerative shock absorber based on the two-leg mechanism; (a) prototype of the two-leg mechanism-based damper; (b) CAD assembly of the proposed prototype.

Other indirect drive based mechanical transmission rotational electromagnetic energy harvesting based damper, known as the Cable-Dynamics Energy Harvesting Shock Absorber (CDEHSA) [17], is shown in Fig. 6. The prototype of the CD-EHSA is illustrated in Fig. 6a, where the linear oscillations of the shock absorber are transformed to rotational motion employing cables, two major pullies (generator pulley and driven pulley), tensors, and end stops, as shown in Fig. 6b. The overall output electrical power (4CD-EHSA in a full automobile suspension model) attained a mean square power of 105 W during a driving speed span of 20–30 km/h, according to the power results of the CD-EHSA prototype.

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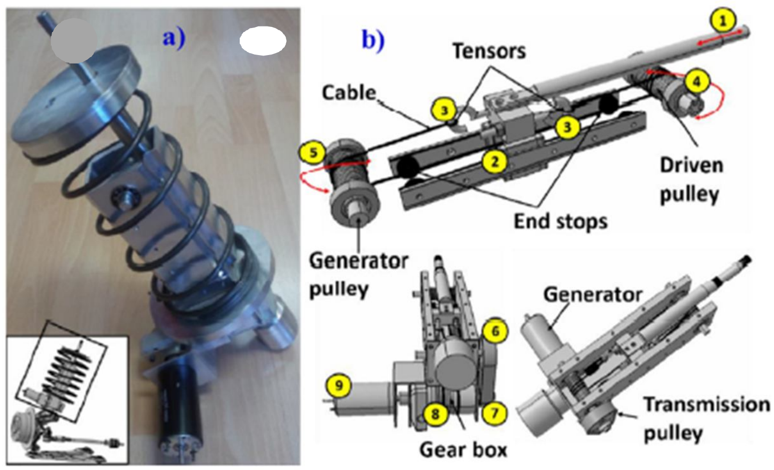
Tang and Zuo [18] also employed a rack–pinion system to translate the building's oscillation to generator rotation, as seen in Figure 7. At the same time, energy collection and vibration control are accomplished. As illustrated in Figure 8, Choi et al. (2009) employed the rack and pinion mechanism to convert the linear motion of a vehicle's shock absorber into rotation to operate the generator. The collected energy is used to regulate and drive an integrated electrorheological (ER) shock absorber with a typical energy usage of 20 W. A passing vehicle's weight engages a ratchet, which drives the flywheel and generator. The electromagnetic generators in this system only rotate in one direction, allowing for direct DC voltage generation without the use of rectifiers.

Yugang Liu et al. [19] presented the design, modelling, and simulation of an energy regenerative shock absorber for transportation vehicles based on twin overrunning clutches to enable energy harvesting from suspension vibration. The suspension vibration input, transmission module, and generator module are the three major components of the energy-regenerative shock absorber. The shock absorber's unique design employs twin overrunning clutches, which may transform oscillatory vibration into unidirectional spinning of the generator.



(a) (b)

Fig. 6. Cable-Pullies transmission based rotary electromagnetic regenerative shock absorber; (a) prototype of the CD-EHSA; (b) CAD assembly, structure and components of the CD-EHSA.

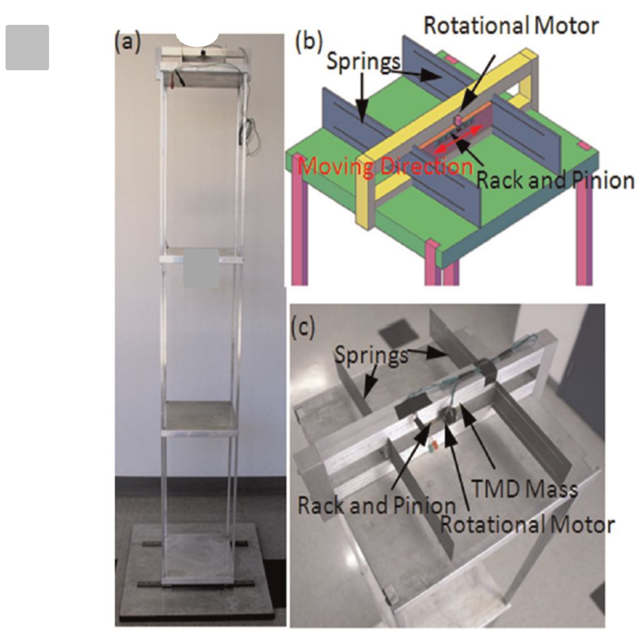


Fig. 7. Energy harvesting from buildings with TMD using rack–pinion mechanism

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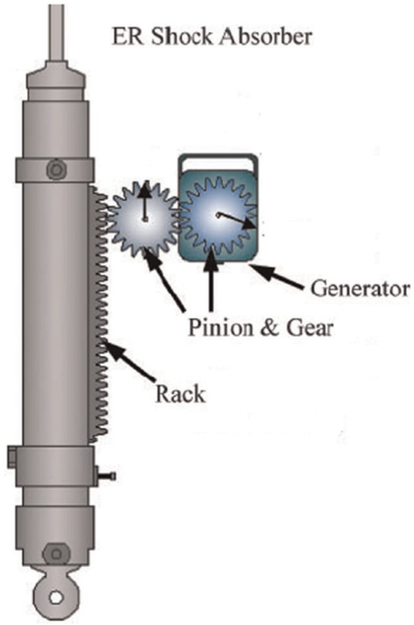

Fig. 8. Self-powered ER damper with rack and pinion mechanism

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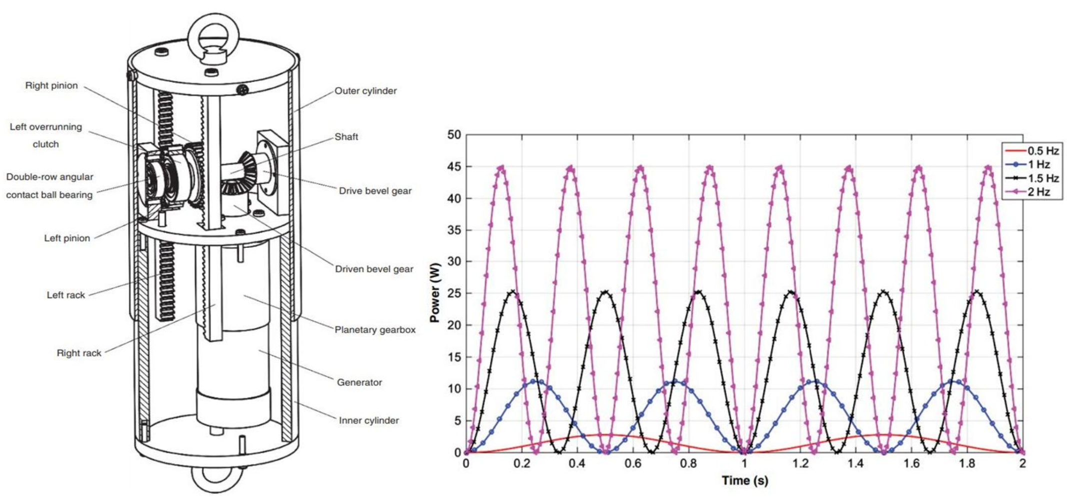
To examine damping properties, the dynamic modelling of the shock absorber is provided. Figure 9 (a) depicts the regenerative shock absorber's detailed components.



(a) (b)

Fig. 9. (a) 3-D model of the transmission mechanism module (b) Output power simulation under different vibrational frequencies with 0.1 V external load, in which the vibration amplitude is 20 mm.

To illustrate the performance of the proposed energy-regenerative shock absorber, simulations were run. At a vibratory input of 2-Hz frequency and 20-mm amplitude, this suggested shock absorber produced a peak output power of 44.73 W and an average power of 22.34 W as shown in figure 9 (b). At 1-Hz frequency and 15-mm amplitude, the prototype achieves 69.19 percent efficiency. The results indicate that varied damping coefficients may be obtained by varying the shock absorber's external load. As a result, the energy-regenerative shock absorber may be used in a variety of transportation vehicles.
Peng Li et al. [20] suggested electromagnetic regenerative dampers or shock absorbers to capture this lost energy and enhance fuel economy. The suspension dynamics using these regenerative dampers can differ considerably from those with traditional dampers. First, unlike traditional hydraulic dampers, electromagnetic regenerative dampers have much higher inertia due to the electromagnetic generator.

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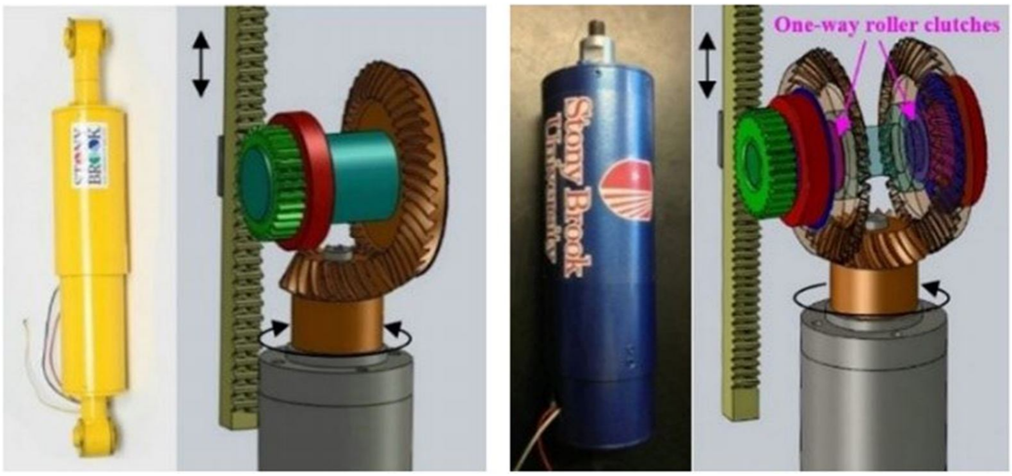
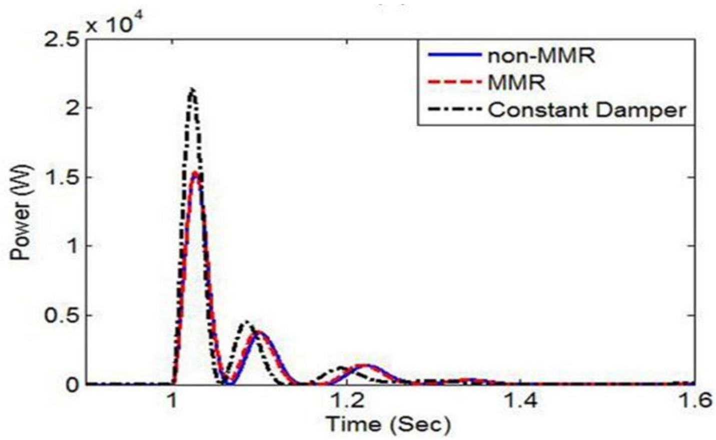
This has a significant influence on suspension dynamics. Second, the damping coefficient of electromagnetic dampers is proportional to the electric load linked to the generator's output and is adjustable. Despite the fact that many designs have been presented, the effects of these sorts of regenerative dampers on vehicle dynamics have yet to be extensively explored. This study models two forms of rotating electromagnetic regenerative dampers, one with and one without a mechanical motion rectifier, and compares their effects on car suspension performance to that of conventional dampers. As seen in Figure 10 (a), both types of electromagnetic regenerative dampers use a rack-and-pinion system to transform linear vibrations into generator rotation.



(a)

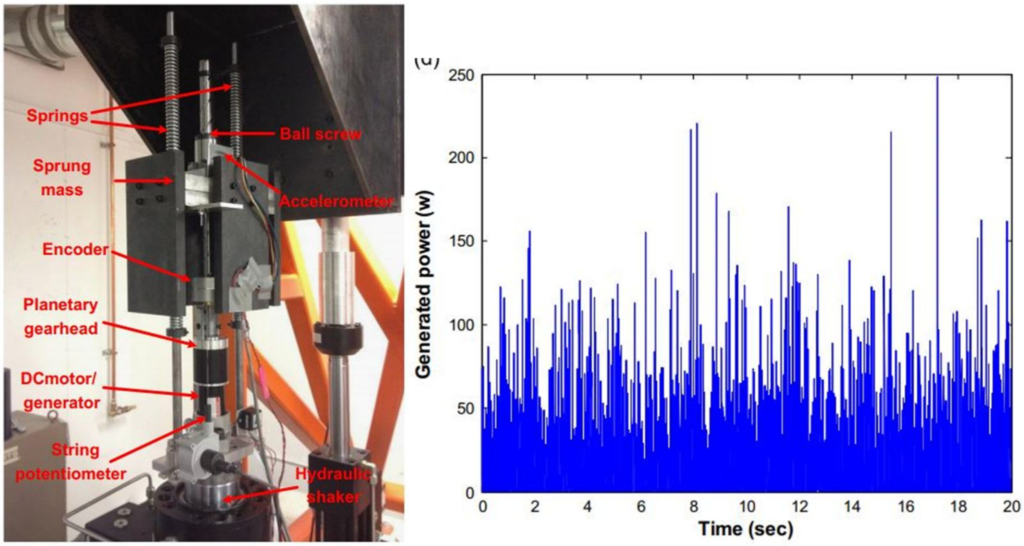


(b)

Fig. 10. Prototypes and schematic diagrams of (a) the non-MMR electromagnetic regenerative damper and the MMR electromagnetic regenerative damper and (b) Comparison of the step responses of the electric output powers

The step responses of the three types of damper are shown in Figure 10 (b). The results demonstrated that, given an optimum equivalent inertia mass, both types of electromagnetic dampers outperform constant dampers in terms of ride comfort. Furthermore, by decreasing the negative effect of the amplified generator inertia, the mechanical motion rectifier mechanism may greatly improve the ride comfort and road-handling performance of electromagnetic regeneration dampers. Furthermore, the energy-harvesting capability of the proposed dampers was tested under International Standardization Organization-defined road profile excitations.
Bo Huang et al. [21] created a vehicle suspension system with energy harvesting capabilities, and he proposes an analytical approach for the system's optimal design. The optimization approach gives design recommendations for estimating stiffness and damping coefficients with the goal of achieving the best performance in terms of ride comfort and energy regeneration. The associated performance measures are the root-mean square (RMS) of sprung mass acceleration and the expected produced power. The real road roughness is regarded as the stochastic excitation described by ISO 8608:1995 standard road profiles, and it is utilised in the optimization technique. Based on the optimization method, an electrical circuit is suggested to offer variable damping in real-time. A test-bed is used, and trials under various driving circumstances are carried out to validate the efficiency of the suggested approach.

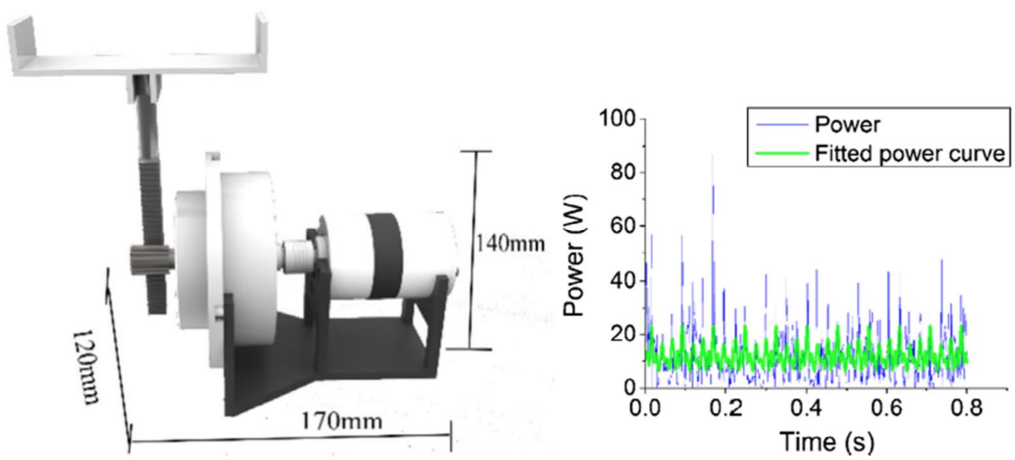
The experimental system, illustrated in Fig. 11, was created to validate the suggested optimization approach.



(a) (b)

Fig. 11. (a) Experimental test setup for the regenerative suspension system. (b) Generated power.

Zhang et al. [22] created and described a sustainable energy-harvesting system that uses a mechanical vibration rectifier to capture energy from train track vibrations (MVR). The MVR is made up of meshing gears and one-way bearings, and it converts bidirectional vibrations into unidirectional rotation to increase transmission efficiency. A DC motor serves as the generator, while a supercapacitors stores the power. The MVR's functioning was modelled and simulated, which included vehicle-track contact, track vibration, the MVR's dynamic response, and an electromechanical study of the generator. Figure 12 (a) shows prototype.



(a) (b)

Fig. 12 (a)Prototype of the proposed renewable vibration energy harvesting system, (b) Output power

The power of generation was reached by using a specified external resistance. The function was discretized using the method, and the curved fit is shown in Fig. 12. (b). The generator's highest output was 86.67 W, while its average power was 12.07 W. This power is appropriate for a wide variety of applications, and the charging time would be reduced to an acceptable range for practical use.

Wang et al. [23] harvested vibration energy from railway rails using a rack–pinion system. Their energy harvesting devices include a unique mechanism that converts bidirectional vibration into unidirectional rotation of the generator; as a result, the harvester's efficiency and longevity may be greatly increased. Figure 27 depicts design and prototype with motion rectifier. The previously stated ball–screw and rack–pinion systems translate bidirectional vibration into alternating rotation of the electromagnetic motor. However, there are several issues.

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For example, when the active vibration control approach was employed, the shock absorber tested in the study by Kawamoto et al. [24] exhibited poor vibration performance at high frequency due to inertia. The alternating motion of the motor and gears will quickly wear out the gears. So, Li and Zuo et al. [25] also proposed using a mechanical motion rectifier, as illustrated in Figure 13, to convert the motor's bidirectional vibration into smooth one-directional rotating motion, resulting in higher efficiency and robustness. Furthermore, if a DC motor is used, the electromagnetic motor will supply DC voltage.

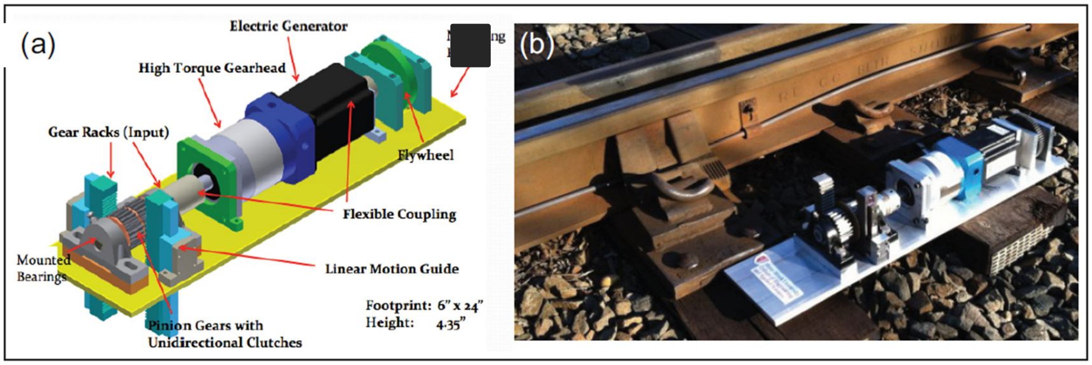


Fig. 13 3-D modeling and prototype Railway energy harvester with motion rectifier and flying wheel

Fluid, in addition to the previously stated linkages, screws, and rack–pinions, is a mechanism for motion transmission. Chandler et al. [26] created a regenerative shock absorber by embedding a turbine into a hydraulic shock absorber. When the fluids flow through the turbine, the displacement and velocity are amplified and communicated to the turbine-driven electromagnetic motor. When tested on a large vehicle, energy was stated to be up to 1 kW, or a 10% gain in fuel economy. However, the driving conditions for the experimental testing are not specified, and the truck's dynamics and vibration mitigation ability are not taken into account. First, the passing vehicle's mechanical force compresses the air in a vessel. The compressed air then constantly drives the generator, harvesting energy indirectly from the traffic bumps. One typical power take off (PTO) technique in ocean wave energy harvesting is to use wave energy to drive pumps that pressurize a hydraulic or pneumatic fluid and then drive a rotating generator via a hydro or air turbine.

Liang et al. [27] In this work, a mechanical motion rectifier (MMR)-based power takeoff system for a wave energy converter is suggested and prototyped. By incorporating two one-way bearings into a rack pinion system, this power takeoff system may transform bidirectional wave motion into unidirectional generator rotation. In this article, a wave energy converter with a 1.2 m buoy and an MMR-based power takeoff system was developed and built. Power takeoff system and single-body wave energy converter models were constructed and studied. The findings of the regular wave simulation demonstrate that MMR-based power takeoff can provide more power than linear damping power takeoff systems, and the optimal PTO damping of the MMR system is less than that of the linear damping system. The MMR, which converts bidirectional motion into unidirectional rotation, is the fundamental mechanism of the PTO system. The MMR's operating concept is seen in Fig. 14. (a). The mechanism of the MMR utilised in the suggested prototype is depicted in Fig. 14(b).

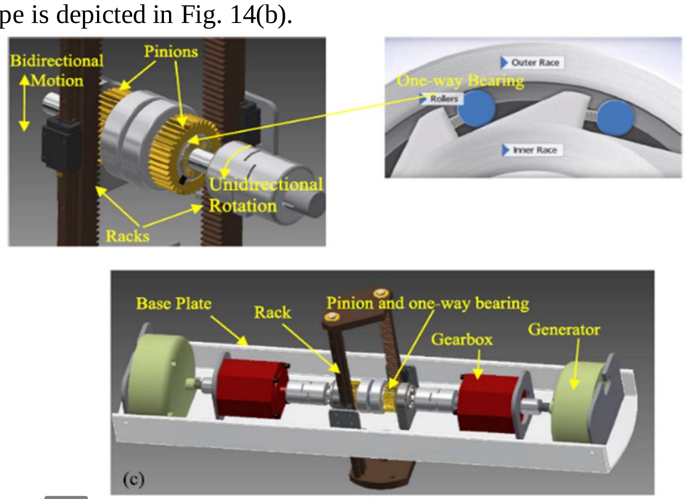
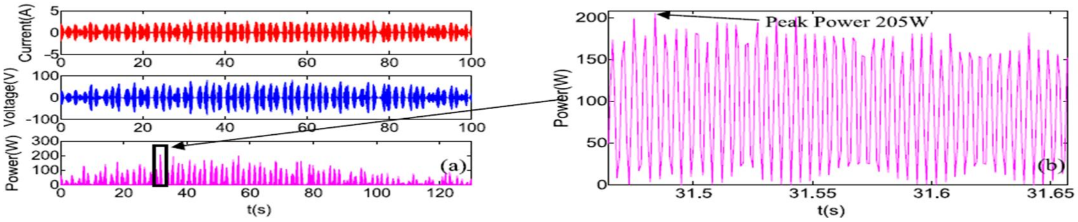


Fig. 14 Mechanism of mechanical motion rectifier (MMR)

The wave height was 0.2 m and the dominant wave period was 4 s as measured by NOAA's Buoy Station 44,039 (41°8′15" N 72°39'17" W). Figure 15 shows the measured current, voltage, and output power from one of the generator's three phases. In one phase, the max output power is 205 W, but the average power is just 21 W. The three phases combined to produce 63 W of average electricity.



(a) (b)

Fig. 15 (a) Recorded voltage, current and output power from one of the three phases of the generator; (b) Zoomed figure for the output power.

Waleed Salman et al. [28] introduced a regenerative absorber for electric cars based on helical gears and twin tapered roller clutches. The absorber can scavenge energy dissipated in the suspension as a result of vibrations caused by road roughness. To accomplish this, the suggested absorber requires three components: the suspension vibration input module, the transmission module, and the generator module. These go between the chassis and the axle. Using a Mechanical Testing and Sensing test fixture, the properties of this handmade prototype with varied helical gear angles are investigated. The bench tests show a peak efficiency of 52% and an average efficiency of 40%, proving that the suggested regenerative absorber is effective and feasible for renewable energy applications in electric cars. As shown in Fig. 16, the absorber is primarily composed of a helical pinion shaft with two helix hands, two helical gears in the different helix hands, two tapered roller clutches, two tapered roller bearings, two guide cylinders, an inner cylinder, an outer cylinder, a joint cylinder, and a generator.

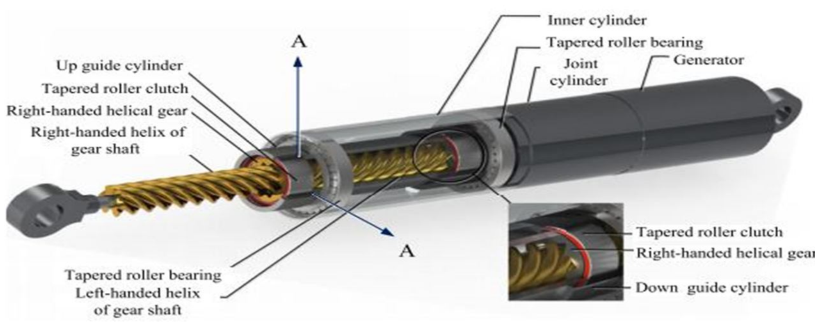


Fig. 16 Details of the regenerative shock absorber

This work constructed a novel high-efficiency energy regeneration absorber using helical gears for purposes such as powering low-wattage electric vehicle devices. Dynamic simulations show that the system has a rapid and consistent dynamic reaction. Furthermore, MTS experiments show that vibration energy may be collected with a predicted peak efficiency of 52% and an average efficiency of 40%. The full-scale prototype shock absorber produced an average output of 270 W at a vibrational frequency input of 2.5 Hz and an amplitude of 5 mm at a helix angle of 45º. The high efficiency and voltage obtained demonstrate that the proposed high-efficiency energy-regenerative shock absorber is capable of producing electricity for applications such as powering low-wattage electrical devices in electric vehicles.

III.CONCLUSIONS

Traditionally, the vibration energy of the vehicle suspension is absorbed as heat by the shock absorber, wasting a significant amount of resources. Regenerative suspensions provide hope for recovering wasted energy. This study examines all types of regenerative suspensions and their characteristics. The potential for vibration energy recovery from automobile suspension was investigated. Converting vibration energy from suspension systems and shock absorbers into electric energy offers a lot of potential for lowering vehicle fuel consumption. Furthermore, the current state of research on regenerative shock absorber structures was described and assessed. Ball screws and rack-and-pinion systems are now the most common structural kinds of regenerative shock absorbers.

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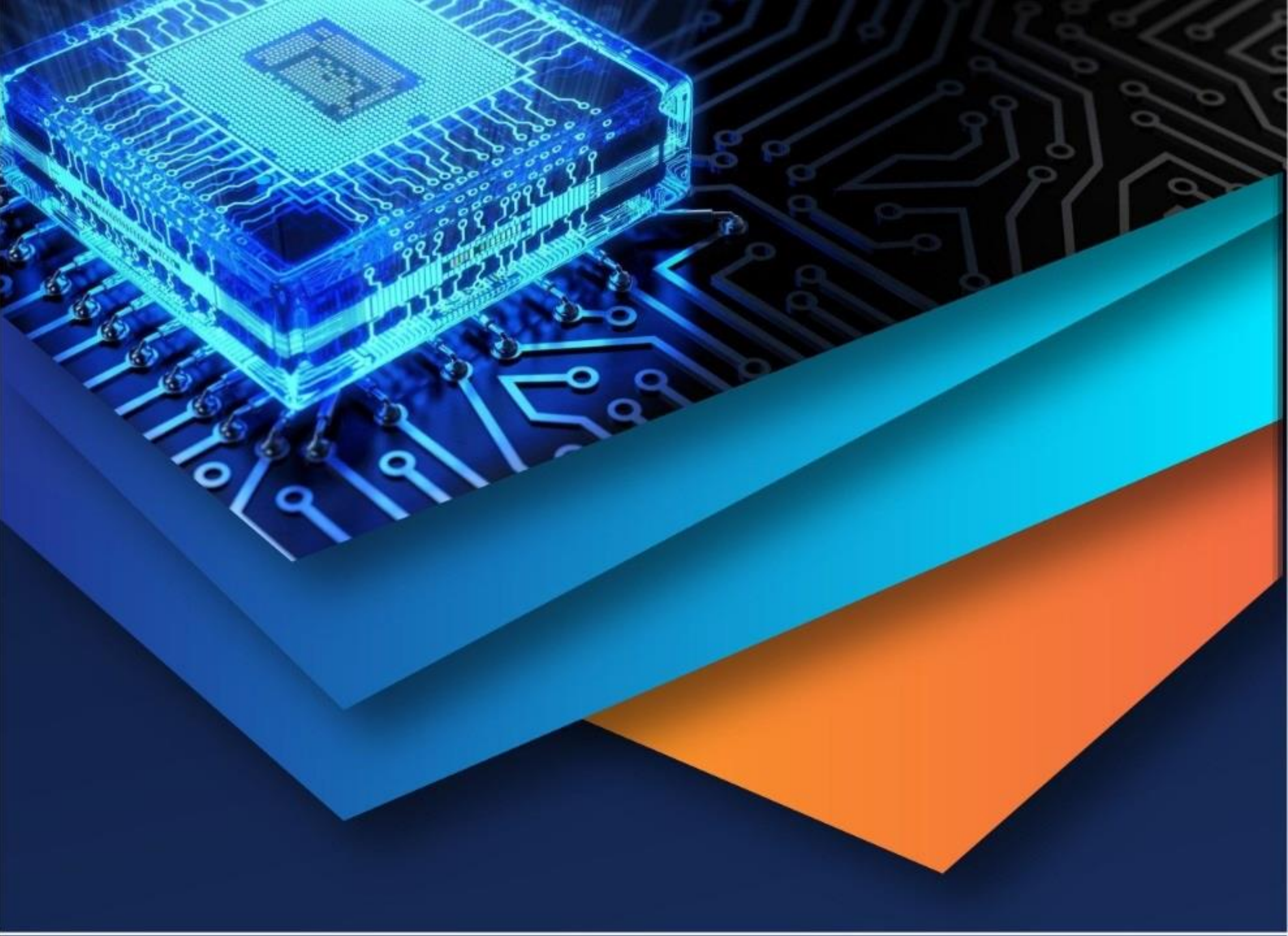

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