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REVIEW ARTICLE

A review on regenerative braking and suspension system

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Abstract

Vehicles are advancing toward energy efficiency and enhanced shock absorption, with suspension systems playing a crucial role in this development. Traditional hydraulic suspension systems dissipate vibration energy as heat to reduce vibrations, which primarily originate from the vehicle's engine. To harness this otherwise wasted energy, energy-recovering suspension systems were investigated to convert manual mechanical energy into electrical energy for powering vehicle components. This article reviews regenerative braking systems with energy recovery capabilities, emphasizing their importance in vehicle energy conservation. Different types of energy-regenerative suspensions are categorized based on their methods of capturing energy, and the current research status on regenerative suspension systems is studied. Key reasons influencing the damping performance and energy recovery parameters of these systems are examined. Unresolved challenges are discussed, providing valuable insights for the further development of methods to capture energy, particularly for hybrid and new energy vehicles.

1. Introduction

As the concept of energy conservation emerged in the 20th century, best method to capture energy, has become a significant focus in the 2-wheeler and 4-wheeler industry. Unlike traditional suspension systems, which passively dissipate vibration energy, Energy-recovering suspension system" s are designed to not only absorb vibrations but it should be useful for work. This energy can then be stored and used as a power source for the vehicle. Current research and advanced technologies have enabled the development of suspension systems with nonlinear and variable stiffness characteristics. These systems provide a smoother ride on even surfaces while effectively absorbing impact energy on rough terrain, thereby isolating and reducing road-induced vibrations transmitted to the vehicle body. Energy-recovering suspension systems are equipped with vibration exciter assemblies to minimize or eliminate vertical vibrations caused by road excitation. These systems convert mechanical energy into electromagnetic energy using actuators, which is then stored in energy storage components. This dual function allows for vibration damping and energy recovery. Furthermore, useful applications have been studied by various research agencies to improve vehicle efficiency and sustainability. While Reference [8] stated that 7.5 KW of energy can be tapped, in the suspension of passenger cars, recreation analysis [7] revealed that the energy recovery of the entire vehicle suspension system was only 46 W. taking into account the main elements affecting the energy-regenerative suspension's recovery efficacy.

At 20 km/h, the immediate highest power is close to 80 W, the street input abundance is 0.01 m, and the frequency is 2 Hz. The front and rear suspensions have respective quick power outputs of about 63 and 43 W. In order to predict the typical distributed force of suspension dampers with different frequencies, we used recurrence and time spaces. The results

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indicated that the typical power corresponds to the typical speed, and the instantaneous power is related to the momentary speed. After over 30 years of extensive innovation and creative advancements, the maximum typical power at a 12 Hz repetition rate has reached 3900 W. Power output also increases as speed rises from 10 km/h to 13 km/h. Energy recovery from suspension systems in various vehicles has been observed: compact cars, off-road vehicles, and transport suspension systems can generate up to 105 W, 384 W, and 1152 W, respectively when traveling at 60 km/h on C-Class asphalt. New energy-powered vehicles face challenges due to current power supply technologies, including limited efficiency, especially in colder climates. These systems strive to enhance the power supply framework through innovative solutions. The Energy-recovering suspension system" plays a key role in reducing vehicle vibrations while improving power supply efficiency by capturing and storing energy from the vibration cycle.

Although only a few studies have explored the effect of vehicle dynamics on energy recovery, most research has focused on road irregularities and driving speed as key factors influencing the energy recovery efficiency of passenger vehicles. Consequently, the influence of vehicle dynamics on the recovery efficiency of energy-recovering suspension systems was also investigated, and the performance of hydraulic energy-recovering suspension systems was analyzed. This paper concentrates on:

- The design of the Energy-recovering suspension system is outlined, and an energy-efficiency model for the hydraulic energy-regenerative suspension is introduced.
- The distinctive features of the two-cylinder safeguard were replicated and dissected, and the effects of vehicle shift boundaries on the water-driven energy-regenerative suspension's recovery capability were subjectively examined.
- Key challenges are identified to address the variations in efficiency observed in existing hydraulic Energy-recovering suspension systems.

The structure of the article is as follows: Section 2 presents the overall design of the Energy-recovering suspension system". Section 3 reviews the current state of energy losses in vehicles. Section 4 discusses the principles of hydraulic and electromagnetic suspension systems with energy recovery, along with their applications in automobiles. Section 5 examines the latest research on hydraulic energy-regenerative suspensions, evaluates the factors influencing vibration damping and energy recovery performance, and highlights some ongoing challenges in suspension energy management.

2. Overall Design Concept of the Energy-recovering suspension system

The Energy-recovering suspension system" is designed to harness and recycle the energy lost during suspension vibrations caused by uneven road surfaces. It consists of three components

2.1 Suspension Vibration Input Module

This component captures kinetic energy generated by the suspension's vibrations and channels it to the transmission module.

2.2 Transmission Module

It converts the bidirectional motion generated by the suspension vibrations into unidirectional motion. This is achieved using a helical gear and a one-way clutch mechanism, ensuring efficient energy transfer.

2.3 Generator Module

The unidirectional motion is used to generate electricity, which can then be utilized to power low-energy devices in electric vehicles. The total Shock-absorbing force of the energy-regenerative shock absorber can be categorized into two types.

2.3.1 Adjustable Equivalent Shock-absorbing force

This is generated by the rotary resistance of the hydraulic motor caused by the generator's back-electromotive force (back-emf). It enables Semi-active suspension control and to adjust the Shock-absorbing force dynamically based on requirements.

2.3.2 Passive Shock-absorbing force

This arises from the resistance during no-load rotation, as well as the passive damping provided by the actuator's Flow channels and oil conduits. A brushless DC generator is used to generate three-phase alternating current (AC), which is then converted into direct current (DC) through a full-wave rectification process, enabling efficient charging of the vehicle's battery. Fig. 1 illustrates the full design of the Energy-recovering suspension system"., showcasing the integration of its key modules and the overall energy-recovery mechanism within the vehicle.

A 2008 report from the US Environmental Protection Agency, in collaboration with institutions like MIT and Ford, revealed that only around 20% of the fuel energy in conventional passenger vehicles is converted into mechanical energy. Furthermore, less than half of that mechanical energy is used to power the driving wheels [12]. In a similar study in 2011, the US Energy Administration analyzed energy flow in a 2005 2.5L Toyota Camry, finding that just 16% of the fuel was effectively utilized to overcome forces such as road friction and air resistance [13].

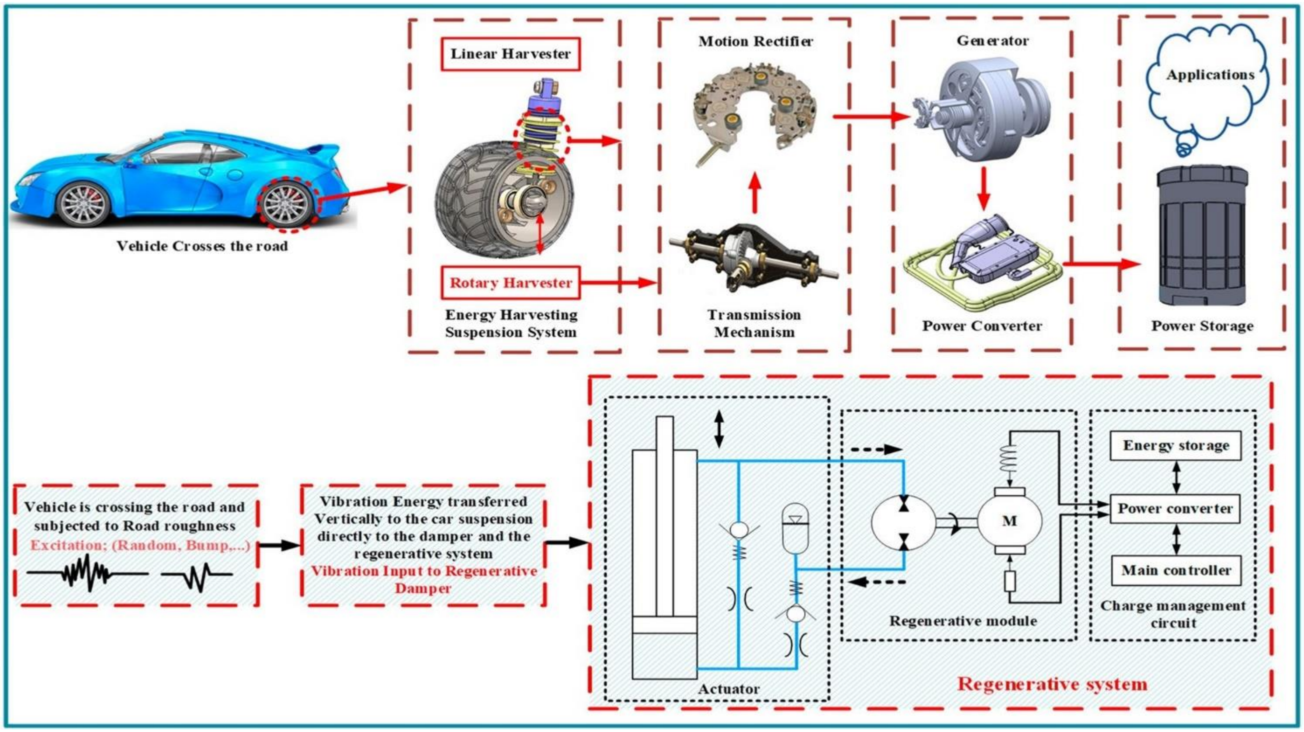

Figure 1: The complete design of the vehicle's Energy-recovering suspension system" (adapted with permission from Ref. [11], © 2018 Elsevier). Research on energy loss status.

The majority of energy loss occurred in the engine, with approximately 75% lost due to heat, pumping, and friction, while tire losses accounted for about 23% [14]. Fig. 2 illustrates the breakdown of vehicle energy consumption. Carruthers [15] also investigated energy dissipation in vehicle dampers under various road conditions and speeds. finding that power losses averaged 80 W during urban driving and 140 W during highway driving. It was noted that, depending on driving conditions, only 12–30% of the fuel consumed by a conventional vehicle is used for propulsion, with the remainder being lost through the engine, transmission, or auxiliary systems. Studies on vehicle energy flow have identified three primary opportunities to enhance fuel efficiency: recovering engine heat, capturing braking energy, and utilizing suspension energy. Bell [16] explored recent developments in vehicle engine waste heat recovery systems in a science publication. Similarly, Briggs [17] examined energy recovery mechanisms in diesel-electric hybrid buses.

Highlighting the contribution of turbo generators to fuel savings, Zhang [18] developed a highly efficient electromagnetic system capable of recovering up to 55.5% of vibrational energy. Salman [19] developed a shock absorber with an average energy recovery efficiency of 40%, achieving a peak efficiency of 52%. Pham [20] designed an active suspension system with energy recovery features, resulting in a reduction of more than 31% in the RMS value of vehicle body acceleration. a 2.8% decrease in energy consumption. Shi [21] proposed a hybrid vehicle suspension model that demonstrated fuel consumption reductions per 100 km of 0.4 L on D-class roads, 0.2 L on C-class roads, and 0.07 L on B-class roads.

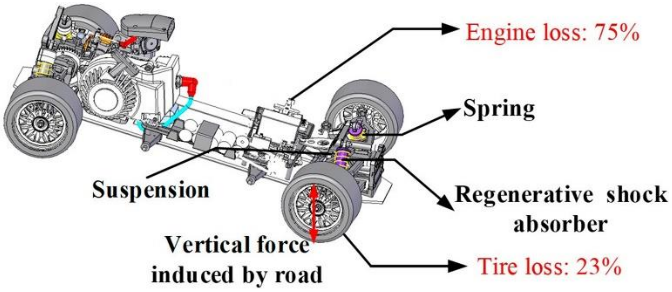

Figure 2: Vehicle energy consumption

3. Advances in Energy-recovering suspension systems

Shock absorbers are essential components of a vehicle's suspension system, providing support to the vehicle body and reducing vibrations to enhance safety and comfort on uneven surfaces. However, a considerable amount of energy is lost during operation through heat, vibration, and friction. To address this inefficiency, Energy-recovering suspension systems have been created to capture and reuse this otherwise wasted energy. Regenerative shock absorbers, designed to harness vibrational energy, have seen substantial advancements and can be categorized into two main types based on their operating mechanisms:

Electromagnetic energy-regenerative suspensions replace traditional shock absorbers with electromagnetic actuators.

As the vehicle encounters uneven terrain, the vibrations cause the motor coil to interact with magnetic induction lines, producing an electric current. This process converts mechanical vibration energy into electrical energy, which is subsequently stored in energy storage devices. The structure and operation of an electromagnetic Energy-recovering suspension system" are depicted in Fig. 4.

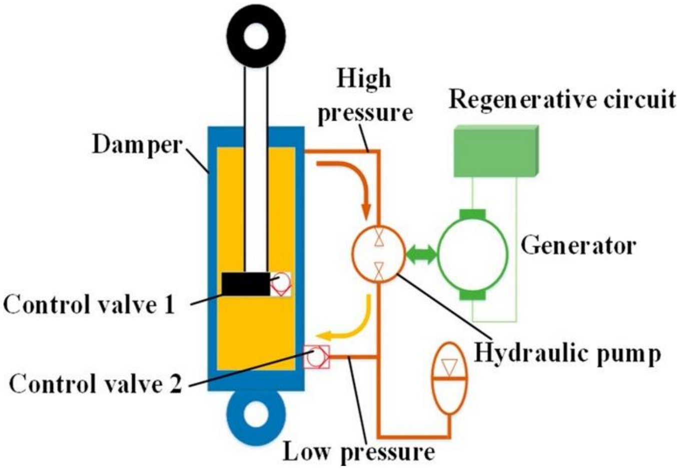

Figure 3: Hydraulic regenerative suspension.

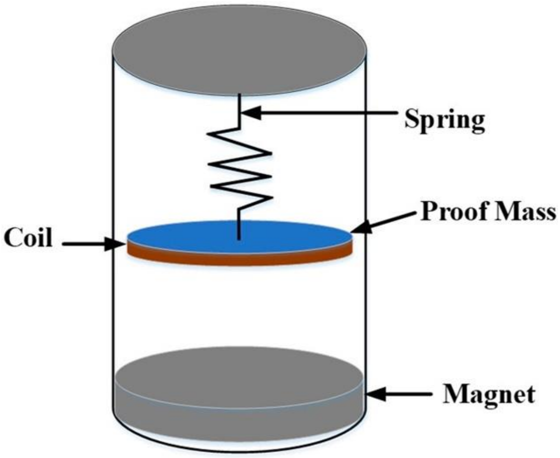

Figure 4: An electromagnetic energy regenerative suspension (Reproduced and drawn with permission [10]

In 1996, Suda and Shiiba introduced a method for energy recovery using a DC generator. Graves et al. [23] developed an Energy-recovering damper that employed a Spinning DC motor and a Ball screw drive system, offering greater efficiency and reduced costs compared to traditional DC generators. Goldner and Zerigian [8] enhanced the design of Electromagnetic dampers that can transform the vertical vibrations of a vehicle into electrical energy. For instance, a standard shock absorber is capable of generating a peak power output of 68 W when the vehicle moves at 30 km/h on smooth campus roads. Martins [6] analyzed hydraulic and electromagnetic active suspensions, highlighting the efficiency of Linear magnetic braking systems used in suspension designs. Li [24] developed a direct-drive brushless tubular actuator that incorporated a passive spring and damper, effectively converting vibrational energy into electrical power using either linear or rotary electromagnetic generators. In a separate study, Li et al. [25] suggested a regenerative shock absorber design that utilizes a rack-and-pinion mechanism for energy conversion. For energy conversion, a power electronic controller is used for real-time damping control and efficient energy conversion. Like regenerative braking, regenerative damping captures mechanical vibration energy and stores it in a battery [26–28]. This system demonstrated a peak power output of 68 W and an average of 19 W, with 300 W of power generation correlating to roughly 1800 W of fuel consumption, considering engine and generator efficiency. For larger vehicles, such as commercial and off-road types, significant potential for energy recovery exists due to their weight and challenging conditions. Liu [29] introduced Electromagnetic suspension systems designed for energy harvesting, which demonstrated an 18% recovery of vibration energy, supplying over 11% of the required power for control functions during road tests on B-class surfaces. Likewise, Roshan [30] tested a damper designed for energy recovery combined with an electronic control unit for power management, maintaining stable damping performance across different levels of vibration intensity. Lei Zuo [31] developed one high-capacity. -density damping mechanism. to improve energy recovery and minimize vibration impact forces. Zuo also introduced a "mechanical motion rectifier" that converted oscillatory motion into unidirectional rotation, achieving 60% recovery efficiency under high-frequency conditions. Zhang [32] designed a two-speed regenerative shock absorber that increased operational speed but faced issues under heavy loads, leading to failure. To address this, Zhang [33] later proposed an indirect-drive damper with an arm gear mechanism, which increased energy output by converting linear to rotational motion, thus boosting entry velocity. Gao [34] analyzed the active damping system energy transfer and developed an electromagnetic suspension strategy that reduced energy consumption by 14.51% while recovering an additional 2.45% of power.

Tucker et al. introduced a fluid-based power generation unit driven by one-way oil flow, improving energy recovery performance and system dependability [35]. Zhang [36] evaluated the suspension efficiency of a shock absorber with hydraulic energy recovery., while Wang [37] achieved a power output of 26 W with 40% efficiency during sinusoidal excitation with a frequency of 1 Hz and an amplitude of 25 mm. At 7.5 mm and 2.5 Hz vibration input, a mean output of 4.3 W was produced [38], with recovery efficiency reaching up to 75%. For passenger vehicles on C-Class roads at 60 mph, regenerative shock absorbers could recover around 300 W of electric energy, while typical car generators produce 500–600 W at approximately 55% efficiency [39]. Zhang [40] designed an ultra-efficient impact dampener" using an ultracapacitor, achieving an efficiency rate averaging 44.24%, with a peak value of 54.98%. A shock absorber utilizing a mechanical motion rectification system was also proposed, converting irregular vibrations into consistent unidirectional rotation, achieving over 60% efficiency at high frequencies and generating more than 15 W of power at 24.14 kilometers per hour.

4. Current Research on Hydraulic Energy-recovering suspension systems

Energy-regenerative shock absorbers are a central component of Energy-recovering suspension systems. With advancements in materials like piezoelectric crystals, these dampers are broadly classified into fluid and magnetic based types [41]. Hydraulic energy-regenerative suspensions, which are simpler in design than electromagnetic systems, were among the first to be adopted. These systems integrate hydraulic devices into traditional shock absorbers, where vertical mechanical vibrations move the piston, generating hydraulic energy that is stored in an accumulator via pipelines and electronic controls [42]. Globally, researchers have made significant strides in developing hydraulic regenerative suspension systems. Glenn R. et al. demonstrated their application in vehicles, showing improvements in performance on rough roads while maintaining passenger comfort through simulation analyses of vibration damping and energy recovery [43, 44]. Kowal et al. evaluated these systems using multifrequency excitation, enhancing damping by incorporating a force generator, leading to a hydraulic regenerative active suspension system [45].

Table 1. Overview of simulation-based studies on energy-regenerative shock absorbers

S.No.	Reference	Road Condition	Model Type	Speed	Generated Power
1	[58]	A-class, B-class, C-class	Minibus	30 km/h	2.08 W, 8.33 W, 33.34 W
		D-class, E-class		30 km/h	133.37 W, 533.21 W
2	[59]	B-class	7-DOF full vehicle	10 m/h, 20 m/h, 30 m/h	42.38 W, 89.53 W, 156.05 W, 193.14 W
		C-class, D-class		10 m/h, 20 m/h, 30 m/h	371.56 W, 684.32 W, 850.64 W, 1712.70 W, 2999.30 W
3	[60]	C-class	Car, Off-road Vehicle	60 km/h	105.2 W, 384 W
		Passenger Car		60 km/h	1152 W
4	[56]	B-class, C-class	Passenger Car	—	100 W, 400 W
		D-class		—	1600 W
5	[46]	Ordinary Road, New Asphalt Road		—	150 W, 3 W
		Rugged Township Road		—	613 W
6	[38]	C-class	Passenger Car	60 m/h	300 W
7	[40]	—	—	24.14 km/h	15 W
8	[61]	B-class, C-class	—	—	≈25 W, ≈100 W
		D-class	—	—	≈410 W
		A-class	—	—	≈10 W
9	[21]	B-class, C-class, D-class	Hybrid Electric Vehicle	—	≈50 W, ≈220 W, ≈790 W

Audi Motors tested regenerative suspensions in passenger cars across different road types. Results showed an average recovery power of 150 W on roads in Germany, 3 watts on smooth Roads, including highways and challenging terrains, can handle up to 613 W alongside a CO_2 emission reduction of 3 g per kilometer [46]. Chen Shian introduced a novel hydraulic Energy-recovering suspension system, analyzing its performance through simulations [47, 48]. Liu [49] designed dampers utilizing a Physical movement conversion system replacing conventional oil dampers with a spherical screw mechanism paired with two unidirectional clutches to enhance energy recovery. Fang et al. improved hydraulic regenerative suspensions by controlling load current to adjust damping coefficients [50]. Li and Peter [51] developed a fluid-based shock absorber with a fluid-powered generator to convert mechanical energy derived from fluid movement into electrical energy. Fang [52] combined fluid and magnetic systems to create a hybrid energy-recovering shock absorber capable of recovering close to 200 W in a 10 Hz frequency with 3 mm displacement. Nevertheless, the efficiency of its energy recovery was limited to 16.6%, with higher excitation frequencies reducing hydraulic rectifier Effectiveness. Guo et al. [53] introduced a pump-based interconnected suspension system that modified oil flow patterns through changes in the cross-linking arrangement. Asadi [54] developed an electromagnetic hybrid shock absorber that also incorporated energy recovery capabilities. Levant Power, a U.S.-based company, conducted extensive research on hydroelectric regenerative shock absorbers. Their application is in vehicles designed for military use and off-road terrain. Improved fuel economy by over 6% and achieved gains Ranging from 7–10% in hybrid and electric vehicles and heavy trucks fitted with energy-recovering shock absorbers. Recovered an average power of 1 kW on standard roads, offering a viable alternative to traditional high-power generators in military and heavy vehicles. Lei and Zhang [56] developed a mathematical model of the "vehicle-road-suspension energy harvesting system," which was designed to assess the potential for energy recovery in vehicles. Suspensions. Using ISO2631-1:1997 to simulate uneven road conditions, they analyzed the energy dissipation of traditional shock absorbers. Their findings revealed that a 1.5-ton passenger car could recover up to reaching 100 W, 400 W, and 1600 W While traveling at 60 mph on B-, C-, and D-class roads, respectively. These estimates represent the maximum recoverable energy, excluding system efficiency and design variations. In traditional dampers, mechanical energy is converted into heat with a fixed damping coefficient. For example, a standard damper in a medium-sized bus traveling on smooth roads at 100 km/h dissipates between 100 W and 400 W. These observations highlight the potential of energy-regenerative suspensions to improve efficiency and reduce energy loss. Traditional dampers, also referred to as shock absorbers, are mechanical devices used to absorb and dissipate the kinetic energy produced by suspension movement in vehicles. These dampers work by converting the energy from the vehicle's motion into heat through hydraulic or pneumatic processes. Key components of a traditional damper include a piston, hydraulic fluid, and a cylinder. As the suspension system moves, the piston moves through the fluid, creating resistance that helps control and dampen the motion. This action helps stabilize the vehicle, enhancing comfort and handling. Typically, traditional dampers are calibrated to specific Shock-absorbing forces to strike a balance between comfort and vehicle performance. However, they do not recover energy; all kinetic energy absorbed is lost as heat. Despite this, traditional dampers remain a reliable and cost-effective solution for many automotive needs. Their performance can be influenced by external factors such as temperature, which can affect the fluid's viscosity.

The output of the Shock-absorbing force in an energy-harvesting suspension system plays a pivotal role in balancing, reducing vibrations, and capturing energy performance. Precise control of the Shock-absorbing force, aligned with suspension parameters across varying excitation frequency ranges, is crucial for maintaining optimal suspension functionality. Lei [56] explored how factors such as road surface irregularities, vehicle speed, suspension rigidity, shock absorber resistance, tire stiffness, and wheel mass influence vehicle efficiency and energy harvesting. The study concluded that Road surface irregularities, tire rigidity, and vehicle speed have a substantial impact on energy recovery. At the same time, suspension stiffness and damping primarily affect comfort and safety. Tire stiffness influences the system's power output, whereas suspension rigidity and shock absorber resistance ensure stability and comfort. Field tests indicated that a medium-sized passenger car traveling while traveling at 60 mph on B- and C-grade roads could recover 100–400 W on average. In contrast, an ultra-compact vehicle driving while traveling at 25 mph on campus streets could recover approximately 60 W.

Zhang and Guo from Wuhan University of Technology [58] analyzed the energy recovery potential of vehicle suspensions using simulations and real-world road tests. They identified tire stiffness, road conditions, and vehicle speed as key factors. Their findings showed that regenerative power was lower on smooth roads (B-Class or better) but increased significantly on rougher roads (C-Class or worse) or in heavy-duty and off-road vehicles.

Zhang [10] investigated the effects of oil temperature on Shock-absorbing force characteristics, finding that prolonged excitation led to a rise in oil temperature, which in turn reduced the Shock-absorbing force. At a sinusoidal excitation speed of 0.52 m/s, the damping oil's equilibrium temperature reached around 105°C. Between temperatures of 20°C and 100°C, the Shock-absorbing force decreased notably, highlighting the critical role of oil temperature in suspension energy recovery performance. Zou [68] developed a suspension system with hydraulic interconnection. Equipped with Shock absorbers with energy recovery capabilities. A full-suspension system with seven degrees of freedom model analysis revealed an efficiency of energy harvesting of 49.87%. Similarly, Zhang [60] developed an electro-hydraulic damper designed for energy harvesting in off-road vehicles. Experimental results indicated that the system's Shock-absorbing force and recovered power were influenced by excitation intensity and external load. At a 10 Ω load and a peak stimulation speed of 0.52 m/s, the damper achieved a maximum power output of approximately 200 W and an average power of 110.6 W. Guan [61] analyzed the dynamic performance of a dual-tube shock absorber and observed that increased stimulation frequencies at a fixed amplitude increased Shock-absorbing force. Similarly, raising vibration amplitude at a constant angular velocity or increasing stimulation frequencies at a fixed amplitude elevated the Shock-absorbing force. Guan also examined the connection between the dynamic damping coefficient and stimulation speed, demonstrating that higher frequencies significantly affect maximum Shock-absorbing force. This research highlights the importance of multiple factors—such as oil temperature, excitation frequency, and vehicle dynamics—in optimizing energy-harvesting suspension systems for enhanced performance and energy recovery.

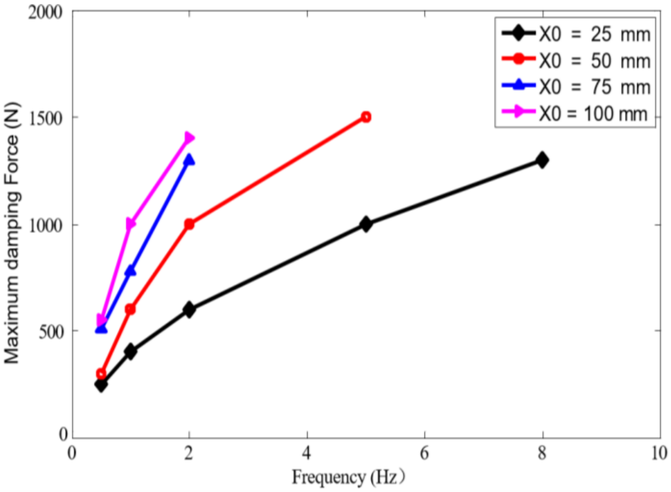

Figure 6. Impact of frequency on the maximum Shock-absorbing force. (Adapted with permission [61], Copyright (2019) Elsevier).

5. Conclusions

The shock-absorbing force output of an energy-recovering suspension system" plays a pivotal role in balancing vibration damping and energy recovery performance. Precise control of the Shock-absorbing force, aligned with suspension parameters across varying excitation frequency ranges, is crucial for maintaining optimal suspension functionality.

Lei [56] explored how factors such as road surface irregularities, vehicle velocity, suspension rigidity, shock absorber resistance, tire flexibility, and wheel weight affect vehicle performance and energy harvesting. The research found that road irregularities, tire flexibility, and vehicle speed significantly influence energy recovery. In contrast, suspension rigidity and damping are more critical for ensuring comfort and safety. Tire stiffness influences the system's power output, whereas suspension stiffness and damping ensure stability and comfort. Field tests indicated that a medium-sized passenger car traveling at 60 mph on B- and C-Class roads could recover 100–400 W on average. In contrast, a super-compact vehicle driving at 25 mph on campus roads could recover approximately 60 W. Zhang and Guo from Wuhan University of Technology [58] analyzed the energy harvesting capacity of vehicle suspensions using simulations and real-world road tests. They identified tire stiffness, road conditions, and vehicle speed as key factors. Their findings showed that regenerative power was lower on smooth roads (B-Class or better) but increased significantly on rougher roads (C-Class or worse) or in heavy-duty and off-road vehicles. Zhang [10] investigated the effects of oil temperature on Shock-absorbing force characteristics, finding that prolonged excitation led to a rise in oil temperature, which in turn reduced the Shock-absorbing force. At a sinusoidal excitation speed of 0.52 m/s, the damping oil's equilibrium temperature reached around 105°C. Between oil temperatures of 20°C and 100°C, the shock-absorbing force decreased significantly, highlighting the critical role of oil temperature in the performance of suspension energy recovery systems.

Zou [68] introduced a hydraulic interconnected suspension system featuring energy-regenerative shock absorbers. A 7-DOF full-suspension model analysis demonstrated an energy recovery efficiency of 49.87%. Similarly, Zhang [60] developed an electro-hydraulic energy-harvesting damper designed for off-road vehicles. Experimental findings showed that the damper's shock-absorbing force and energy recovery were affected by excitation intensity and external load. Under a 10 Ω load and a peak excitation velocity of 0.52 m/s, the damper delivered a maximum power output of around 200 W and an average power output of 110.6

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