Analytical Study on Mechanical Energy Recovery and Utilization of New Energy Vehicles

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Abstract. The pursuit of energy efficiency and sustainability in the automotive industry has become increasingly urgent in response to growing environmental concerns. Herein, this paper focuses on the critical challenge of energy dissipation in new energy vehicles, particularly during braking and suspension vibrations. The paper presents two innovative energy recovery solutions aimed at reducing energy losses and enhancing sustainability. In the realm of sustainable transportation, this study critically evaluates the optimization strategies for braking energy recovery in new energy vehicles. A key recommendation is the integration of a permanent magnet synchronous motor combined with an advanced fuzzy control system. Such an amalgamation not only heightens energy efficiency but also substantially extends the driving range of electric vehicles. Beyond braking energy, the research casts light on an often-overlooked energy source: the vibrational energy from vehicle suspensions. By introducing an innovative electromagnetic damper design coupled with the strategic incorporation of piezoelectric materials, the study unveils avenues to both improve suspension dynamics and transform vibrational energy into usable electrical power. While there are current technological and economic challenges, the ongoing innovations in the design and control processes of new energy vehicles highlight the profound potential within this domain. The insights offered in this context further emphasize the critical need to expand the horizons of sustainable transportation design and management approaches.

Keywords: New Energy Vehicle; Energy Recovery; Brake Energy Recovery; Vibration Energy Recovery.

1. Introduction

In recent years, the world's environmental problems, such as atmospheric pollution, have become increasingly serious [1]. Due to the increasing shortage of fossil energy required for traditional fuel automobile emissions and carbon emissions, new energy vehicles with energy-saving, environmentally friendly and other advantages are bound to be fully accelerated in the world. However, the energy loss problem of new energy vehicles is still significant, of which braking energy and vibration energy are two important parts of energy loss. Braking energy refers to the energy released during the braking process of the vehicle, while vibration energy refers to the energy consumed by the vibration caused by the interaction between the engine, transmission system, wheels and the road surface when the vehicle is running, and the recycling and utilization of these energies have a very high research value for reducing the energy consumption of new energy vehicles. In the process of automobile movement, the vehicle will inevitably produce a lot of mechanical energy, such as the kinetic energy of the vehicle braking and the elastic potential energy of the vehicle suspension undulation. The part of the energy is mostly converted into heat dissipation, resulting in a large waste of energy. Studies have shown that about 1/3 to 1/2 of the driving energy consumed by a car is consumed during braking [2]; at the same time, the waste of vibration energy caused by common oil-liquid dampers accounts for about 17.2% of the total drive energy [3]. This paper will address the energy generated by braking and vibration, propose the use of a permanent magnet synchronous motor and fuzzy control system to reduce the braking energy loss and propose a new electromagnetic damper and a piezoelectric material-based energy recovery device for automobiles to reduce the braking energy consumption.

2. Vehicle Braking Energy Recovery

2.1. Structure, principles and control strategies

There are three common braking energy recovery systems for new energy vehicles: electrical energy storage, hydraulic energy storage and flywheel energy storage. In the field of new energy vehicles, electrical energy storage is the most widely used due to its high energy density, simple structure, and high energy recovery and utilization rate.

The braking energy recovery system of new energy vehicles is mainly composed of a braking system, a motor system, a conversion system and an energy storage system (Figure 1). Braking energy recovery is a process during the deceleration and braking of new energy vehicles. The motor driven by the driving wheel is converted into a generator and stores the generated electrical energy. At the same time, the motor will provide braking feedback to the driving wheel and generate resistance torque, thereby achieving the braking effect. Therefore, this system is also often called a regenerative braking system or a feedback braking system [4].

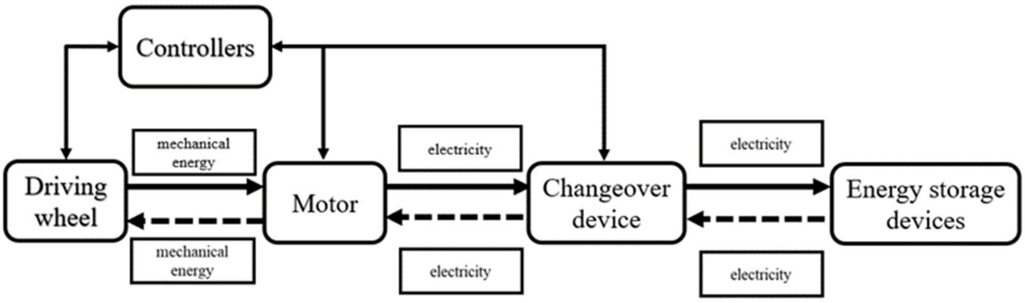

Fig. 1 Schematic diagram of braking energy recovery system for electric vehicles [4]

The braking energy recovery system of new energy has a series type and a parallel type. The working principle of the series braking system is to switch the electric motor to power generation mode when braking, convert the kinetic energy during braking into electrical energy, and store it in the battery or use it for other power needs of the vehicle. This helps reduce heat loss from friction braking and improves overall efficiency. In the parallel braking system, the power system and braking system of the vehicle use independent components. Unlike series brake energy recovery systems, they do not convert the electric motor directly into a generator. Instead, braking systems typically use traditional friction braking, while powertrains use electric motors to provide vehicle power. Overall, parallel brake energy recovery systems are generally simpler but slightly less efficient than series systems at recuperating braking energy. Electric vehicle manufacturers typically select different brake energy recovery system configurations based on their design and performance goals.

Currently, the application of kinetic energy recovery technology in new energy vehicles is still in the stage of continuous optimization and upgrading. In actual applications, the kinetic energy recovery efficiency of different vehicle models may vary greatly. Most brake energy recovery systems are inefficient and require improvement and optimization. The braking energy recovery system is affected by the motor transmission, braking efficiency, and battery energy storage efficiency. This article optimizes the braking energy recovery system from two aspects: selecting a motor with higher performance and better efficiency and optimizing the recovery control strategy.

2.2. Optimizing recovery device based on motor device

In actual operation, it is difficult for the braking energy recovery system to accurately control the charging and discharging current of the energy storage battery, which has various effects on the power battery [5]. Permanent magnet synchronous motors can be selected for improvement. Compared with AC asynchronous motors, permanent magnet synchronous motors have the characteristics of high efficiency, high precision, and low loss and can save 20% of energy. This means that under the same body volume and the same battery capacity, the pure electric cruising range of the permanent magnet synchronous motor will be significantly increased. Permanent magnet synchronous motors are very efficient at converting kinetic energy into electrical energy during the braking process, which helps extend the range of electric vehicles, especially in urban traffic, where they frequently need to brake. The permanent magnet synchronous motor can achieve precise control of the braking energy recovery system, adjusting the degree of energy recovery based on driving conditions and driver's operations, providing better performance and driving experience. The use of permanent magnet synchronous motors to recover energy can reduce the wear of traditional friction brakes and extend the life of braking components. In summary, the use of permanent magnet brushless motors as part of the braking energy recovery system of new energy vehicles can help improve the performance, efficiency and sustainability of the vehicles and provide a better driving experience. This makes new energy vehicles have significant advantages in urban transportation and environmental protection.

2.3. Optimizing recovery device based on the control system

During vehicular braking, varying environments necessitate distinct braking intensities. Inappropriate braking intensities, whether excessive or insufficient, result in energy wastage. To optimize energy conservation during braking and harness the energy produced, it is imperative to judiciously allocate the energy based on real-time conditions to attain maximal efficiency. Leveraging fuzzy control technology for vehicle braking energy recovery emerges as a viable approach, a typical structure of fuzzy control system is shown in Figure 2. This methodology embodies the principle of intelligent control, demonstrating adeptness in managing intricate control systems [6]. The fuzzy control strategy has stronger adaptability. Whether it is urban roads, highways or mountainous roads, the braking energy recovery system can make adjustments according to the actual situation to improve performance and efficiency. The fuzzy control strategy has the ability to respond quickly and can make immediate adjustments according to the driver's operations, providing safer and more effective braking capabilities. Fuzzy control strategies can optimize braking energy recovery to ensure that as much of the kinetic energy generated during braking is converted into electrical energy. The fuzzy control system can effectively handle the uncertainty and ambiguity in the braking system. This is useful in situations where factors such as road conditions, vehicle load and brake component wear are uncertain. In summary, the braking energy recovery system using a fuzzy control strategy has the advantages of strong adaptability, good real-time responsiveness, and efficient energy recovery, which can help improve the performance, safety, and energy efficiency of electric vehicles.

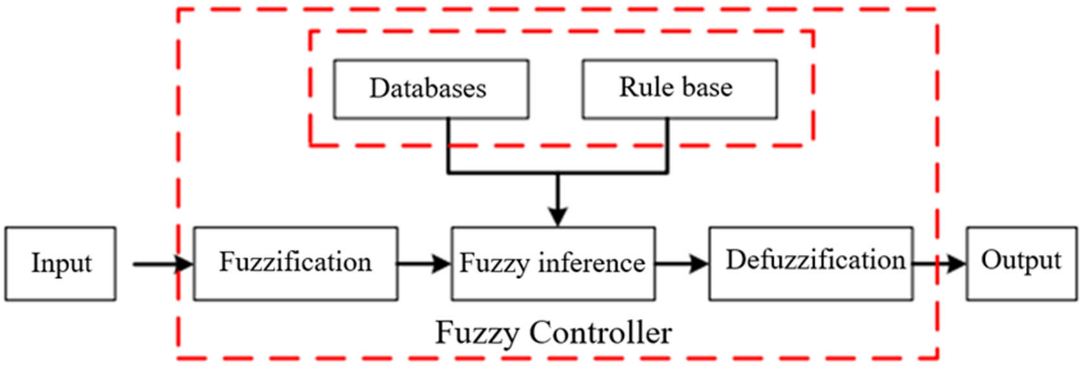

Fig. 2 Structure of fuzzy control system [7]

3. Vehicle suspension vibration energy Recovery

3.1. Vehicle Vibration Energy Analysis

To investigate the recovery of vibration energy in vehicle suspensions, the first step is to analyses the factors that affect such energy. One such factor is the unevenness experienced by the car while travelling on different road surfaces. To describe the statistical characteristics of this factor, it is important to introduce the road power spectral density. According to international standards [8], the mathematical expression for road power spectral density is:

$$G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-w} \tag{1}$$

Where the spatial frequency is denoted as n, while the reference frequency is set at n_0=0.1m^{-1}. The pavement power spectral density value at the reference frequency n0 is represented as $G_q(n_0)$ and referred to as the coefficient of pavement unevenness. Additionally, the frequency index, W, is defined as the frequency of the diagonal line on double logarithmic coordinates. It determines the frequency structure of the pavement power spectral density. The International Organization for Standardization (ISO) suggests in document ISO/TC108/SC2N67 that pavement power spectral density can be classified into eight levels, designated from A to H, based on the degree of pavement unevenness. Typically, urban pavements fall within the first four levels.

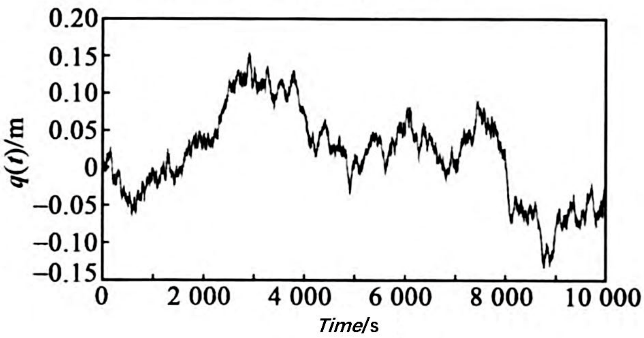

Fig. 3 Unevenness of Class D pavements [9]

Based on the findings of the Class D pavement power spectrum simulation results (refer to Fig. 3) published in literature [9], it can be concluded that urban pavements are susceptible to random vertical vibrations of up to ±0.15 m. As tires separate the wheels of a car from the road surface, and the shock absorbers are more elastic than the tires under normal tire pressures, changes in road surface unevenness can be approximated as changes in the vertical displacement of the wheels. Furthermore, as the suspension is connected to the hub, a range of vehicle suspension vibration amplitudes can be calculated for general conditions.

3.2. Vehicle Vibration Energy Analysis

Following the analysis of vehicle vibration, a new electromagnetic damper based on a rotary motor [10] has been designed as a feasible recovery device to enhance the suspension damper (Figure 4). This design solution not only effectively adjusts the damper's damping in accordance with the road surface conditions, producing a clear vibration-damping effect, but also recovers vibration energy, converting it into electrical energy for storage. The dynamic model and mechanism of the electromagnetic damper are illustrated in Figure 4. The electromagnetic torque generated by the motor serves as the source of the damper's output force. The ball screw component facilitates the conversion of the linear motion of the damper and rotary motion of the motor shaft, and subsequently transforms the motor's torque into the damper's output force.

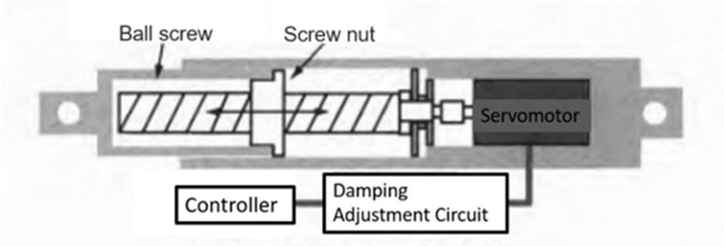

Fig. 4 Electromagnetic damper model [10]

The scheme utilises a DC chopper circuit with lifting voltage to control the circuit. This circuit topology allows for adjustable voltage at the output, as illustrated in Fig. 5. When the MOSFET power switching tube is enabled, the input voltage (Vin) is supplied to the inductor coil (Lf) to store energy. The current (i_{in}) simultaneously powers the capacitance (Cf) to maintain a consistent output voltage and supply power to load (R). When disconnecting the power field effect transistor MOSFET, the inductor coil's energy is released to the load R, resulting in the current i_{out}. The load voltage V_{out} is opposite to the polarity of the power supply voltage, and this circuit is known as DC-to -DC converter. In practical applications, adjusting the duty cycle α of the PWM signal driving the MOSFET enables the output voltage to be modified based on the input voltage.

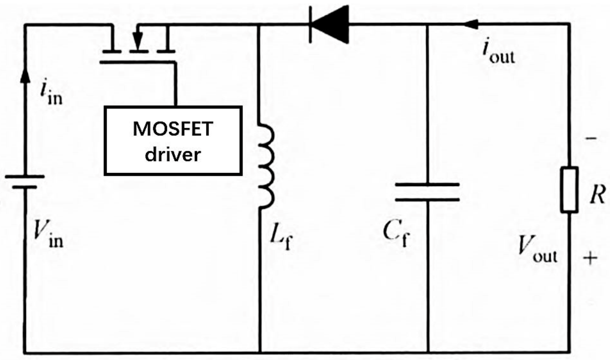

Fig. 5 DC-to -DC converter schematic diagram [10]

This design strategy utilises the motor's reverse electromotive force as the DC-to-DC converter's input voltage. To achieve electrical energy storage, the variable resistance load is substituted with a battery. As per the simulation analysis data concerning the 1/4 suspension [10] (Fig. 6), the output voltage amplifies as the resistance value increases. This occurs when the motor load is variable resistance whilst under the same sinusoidal excitation. After conducting numerical calculations, it has been determined that the full-suspension system is capable of generating a peak power output of approximately 184 watts. This suggests that the aforementioned scheme possesses significant potential for energy recovery.

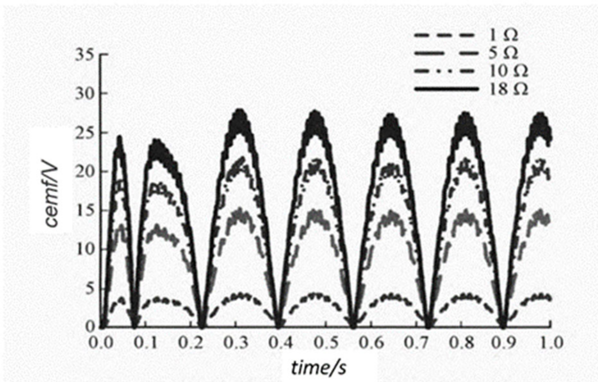

Fig. 6 Experimental results of variable resistance load [10]

The improved scheme offers the advantage of effectively converting vibration energy into electrical energy and storing it using a battery as an energy storage device. Additionally, the scheme enables high-frequency and efficient electromagnetic suspension damping adjustment with minimal energy consumption, thereby enhancing the vibration attenuation effect across different road surfaces. However, this solution has some limitations. For instance, the design of the new electromagnetic damper and circuit control system could escalate the vehicle's manufacturing cost. Similarly, the augmented electrical and electronic components could elevate the maintenance and repair complexities to some extent.

3.3. Vehicle Vibration Energy Analysis

In addition to improving the structural function of existing automobile suspensions, recovery of suspension vibration energy can also be, from the point of view of improving the materials used for suspension manufacturing, developed a piezoelectric material-based automobile energy recovery device.

Piezoelectric materials are a special class of functional materials that can generate an electrical charge when subjected to pressure or stress. At the same time, deformation or vibration occurs when a voltage is applied. Therefore, this material is very good at converting mechanical energy into electrical energy and electrical energy into mechanical energy. This property makes piezoelectric materials have many potential applications in vehicle suspension systems.

First, piezoelectric materials can be used for energy recovery and reuse. In conventional vehicle suspension systems, shock absorbers absorb and dissipate vibration energy through damping, and this energy is usually lost as heat. By introducing piezoelectric materials into the suspension beam system, the vibration energy can be converted into electrical energy and recycled. The vehicle can then utilize this energy to power components such as on-board electronics or rechargeable batteries, thereby improving energy efficiency.

The electrical energy generation mechanism of piezoelectric energy recovery systems is based on the positive piezoelectric effect of piezoelectric materials. The piezoelectric effect is a phenomenon in which mechanical energy is interchanged with electrical energy in materials.

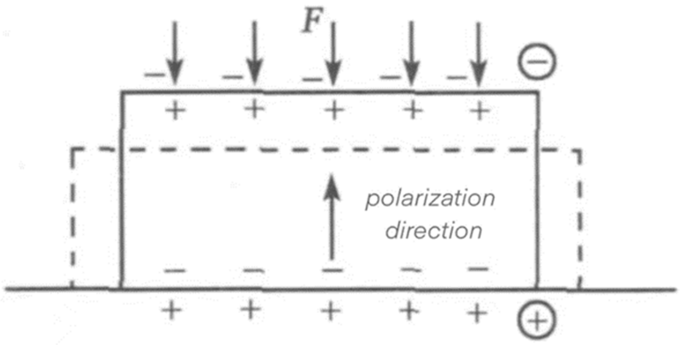

Fig. 7 Schematic diagram of the positive piezoelectric effect [11]

They are usually attached to the vibration-extracting mechanical structure in practical applications. In this way, the mechanical energy of the surrounding vibration is first transferred to the piezoelectric material through the structure to deform it, thus generating electrical energy by utilizing the positive piezoelectric effect. Usually, in practical application, it is pasted on the vibration-extracting mechanical structure so that the mechanical energy of the surrounding vibration is firstly transferred to the piezoelectric material through the vibration-extracting structure, and finally, the positive piezoelectric effect is utilized to generate electric energy (Figure 7).

In order to improve the efficiency of energy conversion, an optimized design of the vibration extraction structure is required. Double or multi-layer piezoelectric structures can increase the effective volume of the piezoelectric body, thus realizing a piezoelectric energy recovery system with small volume and high recovery efficiency. The three piezoelectric structures are shown in Figure. 8 [11].

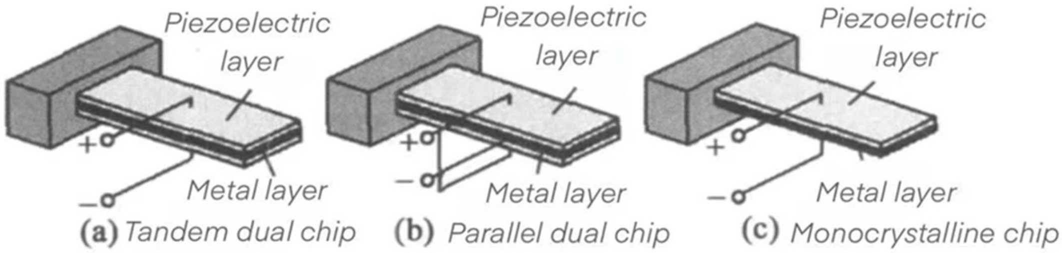

Fig. 8 multi-layer piezoelectric energy recovery device [11]

The first type of piezo dual chip connects 2 piezo outputs in series, while the second type connects 2 piezo outputs in parallel. The results of the study [11] show that the piezoelectric single wafer produces higher energy when the load is small, and the frequency of the excitation force is low; the parallel piezoelectric double wafer outputs higher energy when the load impedance and the frequency of the excitation force are moderate; and the series piezoelectric double wafer outputs higher energy when the load impedance and the frequency of the excitation force are high.

In summary, this paper proposes a novel way of utilizing piezoelectric materials to recover vibration energy, which is combining a piezoelectric energy recovery device with the piston of a decompression damper and connecting two piezoelectric sheets in series above and below the base plate. Part of its structure is shown in Figure 9. This device can utilize the impact energy carried by the damping fluid in the hydrodynamic shock absorber repeatedly flowing through the damping holes when the car is moving and then convert this part of the mechanical energy into electrical energy, which can be stored in the car battery or directly supplied to the on-board low-power electrical appliances at the same time, without changing the normal driving experience [12].

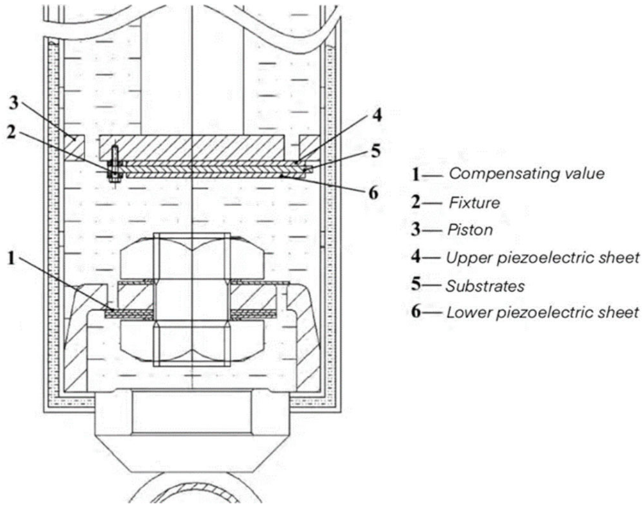

Fig. 9 Schematic diagram of shock absorber structure [12]

By combining the piezoelectric material with the piston, the suspension system can convert the vibration energy during the vehicle driving process into electrical energy, realize the recovery and reuse of energy, so as to improve the efficiency of energy utilization and reduce the waste of energy. At the same time, the introduction of piezoelectric energy recovery device can transform the suspension system into an energy generation system. By maximizing the piezoelectric effect, mechanical energy can be converted into electrical energy, and the energy utilization efficiency of the vehicle can be improved by storing and supplying the electrical demand.

4. The Comparison between ICE and Hybrid Engine

This paper presents a comparative analysis of fuel engines and hybrid engines in terms of fuel efficiency, environmental impact, cost effectiveness and performance. In terms of fuel efficiency, oil-powered engines running solely on conventional fuels such as petrol or diesel have been the standard for automotive propulsion for decades. However, hybrid engines, which combine ICE and electric propulsion, have shown significant improvements in fuel efficiency. By utilizing electricity in low demand driving conditions, hybrid vehicles can significantly reduce fuel consumption, typically achieving fuel economy figures that are 25% to 50% higher than their conventional counterparts [5]. The environmental impact of these engines also varies greatly. Conventional engines emit large amounts of greenhouse gases and pollutants due to their reliance on fossil fuels [5]. In contrast, hybrid engines reduce emissions by supplementing or replacing fuel combustion with electricity [5]. This reduction in emissions is consistent with global efforts to mitigate climate change and reduce air pollution, making hybrid technology a more environmentally friendly option [5].

In terms of cost-effectiveness, while hybrid engines typically have a higher initial purchase price due to their complex systems, they can deliver long-term savings through reduced fuel consumption. Initial costs are further offset by many regional government incentives and rebates for hybrid vehicles. Fuel-burning engines, while typically having a lower upfront cost, may not provide the same level of savings over the long term, especially if fuel prices rise [6]. In terms of performance, conventional fuel engines typically offer higher power output and are more responsive in certain driving conditions [6]. However, hybrid engines have the advantage of instant torque from the electric motor for smooth acceleration and enhanced driving performance [6]. The integration of electric and fuel propulsion in a hybrid vehicle allows for balanced performance that can be customized to suit a variety of driving needs [6].

In summary, the comparative analysis of fuel and hybrid engines illustrates the relationship in multiple ways. While fuel engines remain a reliable and familiar technology, hybrid engines offer a compelling alternative that can improve fuel efficiency, environmental stewardship, and, in many cases, cost-effectiveness. The choice of these engine types may depend on personal preferences, driving habits, and broader social and economic factors. As technology continues to advance, the dynamics of comparisons between these engines are likely to change further, reflecting continued innovation and changing priorities in the automotive industry.

5. Conclusion

In tackling the issue of energy dissipation in new energy vehicles, particularly the dissipation of braking and vibration energy, we analyze two energy recovery schemes. The initial improvement we executed was on the braking energy recovery system for new energy vehicles, which employs a permanent magnet synchronous motor and a fuzzy control system to effectively reclaim the mechanical energy produced during braking. Secondly, we examined the process of harnessing vibration energy from a vehicle's suspension system, which is then converted into electrical power and stored using a new electromagnetic damper and a device based on piezoelectric material. These solutions not only offer significant and highly effective energy recovery capabilities, which help to minimize energy wastage and prevent environmental harm, but also exemplify the latest advancements in new energy vehicle technology. Although some of these solutions are currently constrained by manufacturing technology and economic costs, it is thought that by persistently enhancing and innovating the structural design and internal energy control methods of new energy vehicles, more eco-friendly and efficient new energy vehicles will emerge in the future, thereby taking an important stride towards a more sustainable transport system.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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