

Design and Development of Regenerative Suspension System Using Rack and Pinion Mechanism

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Abstract - Conventional vehicle suspension systems dissipate a considerable amount of vibration energy in the form of heat during damping, leading to continuous energy loss. The present work focuses on the design and development of a regenerative suspension system capable of converting this wasted mechanical vibration energy into useful electrical energy using a rack and pinion mechanism.

The developed system consists of a coil spring, rack and pinion arrangement, DC generator, and supporting frame structure. The vertical motion of the suspension caused by road irregularities is converted into rotational motion through the rack and pinion mechanism, which subsequently drives the generator for electrical power generation.

The prototype model was fabricated and tested under simulated vibration conditions. Experimental observations indicate that the output voltage varies from 7 V to 26 V depending on the rotational speed and vibration intensity, with a maximum generator speed of 60 RPM. The system was designed considering a vibration frequency range of 1–2 Hz, representing typical suspension behavior under normal and moderately rough road conditions.

The obtained results demonstrate the feasibility of harvesting vibration energy from vehicle suspension systems. The proposed system is simple, compact, cost-effective, and suitable for implementation in modern automobiles, especially electric and hybrid vehicles, to improve overall energy utilization and reduce energy wastage.

Keywords: Regenerative Suspension System, Energy Harvesting, Rack and Pinion Mechanism, Vibration Energy, DC Generator, Automotive Suspension.

I. INTRODUCTION

The rapid growth of the automotive industry has significantly increased energy consumption and environmental concerns worldwide. Modern vehicles are designed to provide better ride comfort, stability, and safety through advanced

suspension systems. The primary function of a suspension system is to absorb shocks and vibrations caused by uneven road surfaces and maintain proper tire contact with the road.

In conventional suspension systems, the vibration energy generated during vehicle motion is dissipated in the form of heat through dampers and shock absorbers. Although this improves ride comfort, a considerable amount of mechanical energy is wasted continuously without being utilized. With increasing emphasis on sustainable transportation and energy conservation, researchers have focused on recovering this wasted vibration energy and converting it into useful electrical energy.

Regenerative suspension systems provide an effective solution by integrating energy harvesting mechanisms into vehicle suspension systems. These systems convert the vertical motion of the suspension into electrical energy that can be used to power auxiliary vehicle components or stored in batteries. Different regenerative suspension technologies such as hydraulic systems, electromagnetic systems, and rack and pinion mechanisms have been developed for this purpose.

Among these methods, rack and pinion mechanisms are widely preferred due to their simple construction, compact design, low manufacturing cost, and ease of fabrication. The mechanism converts linear motion into rotational motion, making it suitable for driving a generator. The generated electrical energy can be used for low-power automotive applications, thereby improving overall energy efficiency.

The present project focuses on the design, fabrication, and testing of a rack and pinion based regenerative suspension system. The system consists of a spring-damper arrangement, rack and pinion setup, DC generator, and supporting frame structure. Experimental testing was conducted under simulated vibration conditions to analyze voltage generation at different rotational speeds.

The obtained results demonstrate that the developed system can effectively convert vibration energy into electrical energy. The project highlights the potential application of regenerative suspension systems in modern automobiles,

particularly in electric and hybrid vehicles where efficient energy utilization is highly important.

II. LITERATURE REVIEW

The development of regenerative suspension systems has attracted significant research interest due to the increasing demand for energy-efficient automotive technologies. Researchers have investigated different mechanisms to recover vibration energy from vehicle suspension systems and convert it into usable electrical energy.

Conventional suspension systems dissipate vibration energy in the form of heat through damping mechanisms. Regenerative suspension systems aim to recover this wasted energy using mechanical, hydraulic, or electromagnetic conversion systems.

2.1 Regenerative Suspension Systems

Regenerative suspension systems are designed to harvest mechanical vibration energy generated due to road irregularities and convert it into useful electrical energy. These systems improve overall vehicle energy efficiency by utilizing energy that is otherwise wasted.

Different regenerative suspension technologies have been developed such as hydraulic regenerative systems, electromagnetic regenerative systems, and mechanical regenerative systems. Hydraulic systems offer high energy recovery but are complex and expensive. Electromagnetic systems provide good efficiency but require advanced control systems.

Mechanical regenerative systems using rack and pinion mechanisms are widely preferred for prototype-level applications due to their simplicity, compactness, and low manufacturing cost. The rack and pinion mechanism converts vertical suspension motion into rotational motion suitable for electricity generation.

2.2 Rack and Pinion Mechanism

The rack and pinion mechanism is one of the simplest and most effective motion conversion mechanisms used in regenerative suspension systems. The vertical linear motion generated in the suspension system moves the rack vertically, which rotates the pinion gear connected to a generator shaft.

The rotational motion produced by the pinion drives a DC generator, converting mechanical energy into electrical energy. The simplicity of the mechanism makes it suitable for small-scale applications and prototype development.

Researchers have reported that rack and pinion regenerative suspension systems can generate power outputs ranging from a few watts to several hundred watts depending on vibration conditions and system design.

2.3 Existing Research Studies

Zhang *et al.* developed a rack and pinion based regenerative shock absorber capable of generating electrical power under varying vibration conditions. Their study demonstrated power generation between 10 W to 200 W depending on vibration amplitude and frequency.

Ali *et al.* improved regenerative suspension efficiency by optimizing gear ratios and reducing transmission losses in rack and pinion systems.

Al-Yafeai *et al.* reviewed different regenerative suspension technologies and concluded that rack and pinion mechanisms provide an effective balance between efficiency, simplicity, and cost.

Recent studies also indicate that regenerative suspension systems can contribute to improved fuel economy and reduced emissions in electric and hybrid vehicles.

2.4 Research Gap

Although several regenerative suspension systems have been developed, many existing systems are complex, expensive, and difficult to implement in small-scale automotive applications. Most systems focus on electromagnetic or hydraulic energy harvesting mechanisms which require sophisticated control systems and high manufacturing costs.

Limited research has been conducted on simple and low-cost rack and pinion based regenerative suspension systems suitable for prototype-level and small vehicle applications. Additionally, experimental validation under practical operating conditions remains limited.

Therefore, the present work focuses on developing a compact, cost-effective, and experimentally validated regenerative suspension system capable of generating usable electrical energy from vehicle vibrations.

III. EXPERIMENTAL SETUP

The developed prototype consists of a rack and pinion mechanism integrated with a coil spring, DC generator, supporting frame, and electrical output circuit. The vertical motion applied to the suspension system causes linear movement of the rack, which rotates the pinion connected to the generator shaft.

The prototype was tested under simulated vibration conditions by manually applying vertical displacement to the suspension assembly. Voltage readings were measured at different rotational speeds using a digital multi meter.

The generated electrical energy was used to power an LED module, demonstrating the practical feasibility of the system. The methodology adopted for the development of the regenerative suspension system was planned systematically to ensure efficient conversion of vibration energy into electrical energy. The complete methodology includes problem identification, literature review, concept selection, system design, fabrication, testing, and performance evaluation.

Initially, the energy loss occurring in conventional suspension systems was studied. It was observed that large amounts of vibration energy generated due to road irregularities are dissipated as heat through shock absorbers. To overcome this issue, regenerative suspension technology was considered for energy harvesting.

A detailed literature review was conducted to study existing regenerative suspension mechanisms such as hydraulic, electromagnetic, and rack and pinion systems. Based on simplicity, compactness, low manufacturing cost, and ease of fabrication, the rack and pinion mechanism was selected for the present work.

The proposed system converts the vertical linear motion of the suspension into rotational motion using a rack and pinion arrangement. The rotational motion drives a DC generator connected to the pinion shaft, thereby generating electrical energy.

The prototype model was fabricated using mild steel square pipes for the supporting frame structure. Major components used in the system include a coil spring, rack, pinion gear, DC generator, bearing arrangement, and electrical output circuit.

The fabricated prototype was tested under simulated vibration conditions. Vertical displacement was manually applied to the suspension setup to simulate road-induced vibrations. During experimentation, voltage generation was measured at different rotational speeds using a digital multi meter.

Finally, the experimental results were analyzed to evaluate system performance, voltage generation capability, and feasibility for practical automotive applications.

3.1 Working Principle

The working principle of the regenerative suspension system is based on the conversion of mechanical vibration energy into electrical energy. When a vehicle moves over uneven road surfaces, vibrations are generated in the suspension system. These vibrations produce vertical linear motion in the spring-damper arrangement. The linear motion causes the rack to move vertically. The rack engages with the pinion gear, converting linear motion into rotational motion. The rotating pinion shaft is mechanically connected to a DC generator.

As the generator rotates, electrical energy is produced due to electromagnetic induction. The generated electrical energy can be used to power small electrical devices or stored in a battery for future use.

The proposed mechanism effectively utilizes otherwise wasted vibration energy and improves overall energy efficiency.



Figure 1: Prototype



Figure 2: Rack and Pinion

3.2 Components of the System

The regenerative suspension system consists of several mechanical and electrical components integrated together for energy conversion. Each component performs a specific function in the overall operation of the system.

- 1. Coil Spring:** The coil spring absorbs shocks and vibrations generated due to external excitation. It provides the required vertical motion for the system.
- 2. Rack:** The rack converts vertical linear motion into translational movement required for pinion rotation.
- 3. Pinion Gear:** The pinion gear meshes with the rack and converts linear motion into rotary motion.
- 4. DC Generator:** The DC generator converts rotational mechanical energy into electrical energy.
- 5. Supporting Frame:** The supporting frame provides structural stability and supports all components.
- 6. Electrical Circuit:** The electrical circuit includes connecting wires, output terminals, and LED indicators for voltage observation.

3.3 Experimental Setup

The experimental setup consists of the fabricated regenerative suspension prototype integrated with a DC generator and electrical measuring instruments. The setup was designed to simulate suspension vibrations under laboratory conditions. Vertical displacement was manually applied to the suspension mechanism to generate oscillatory motion. The rack and pinion arrangement converted the linear motion into rotational motion which drove the generator. A digital multi meter was used to measure output voltage generated at different rotational speeds. The generated electrical energy was also utilized to power an LED, demonstrating practical energy harvesting capability. The experiments were conducted for different vibration intensities and rotational speeds to evaluate the system performance.

Table 1: Components and Specifications

Component	Specification
Coil Spring	Mild Steel Compression Spring
Rack	Straight Teeth Rack
Pinion Gear	Spur Gear
DC Generator	12V DC Motor/Generator
Frame Material	Mild Steel
Output Voltage	7V – 26V

Maximum RPM 60 RPM

IV. DESIGN ASSUMPTION

The following assumptions were considered during design calculations:

- Effective mass supported by suspension (m) = 5 kg
- Vibration frequency (f) = 2 Hz
- Displacement amplitude (x) = 0.08 m
- System efficiency (η) = 70%
- Radius of pinion gear (r) = 0.02 m
- Gravitational acceleration (g) = 9.81 m/s²
- Maximum generator speed = 60 RPM

Design Values for Regenerative Suspension System

- Rack & Pinion Material: EN8 / EN24 / 4140 Steel
- Module (m): 1.5 – 2 mm
- Number of teeth (z): 18 – 24
- Pitch diameter: 36 – 40 mm
- Rack length: \geq 250 mm
- Shaft diameter: 10 – 12 mm
- Mounting plate thickness: 6 – 10 mm (MS Plate)

System Parameters

- Effective vibrating mass: 5 kg
- Suspension frequency: 2 Hz
- Suspension travel (stroke): 80 mm
- Pitch radius: 20 mm
- Pitch diameter: 40 mm
- Factor of safety: 1.5 – 2

Spring & Force Calculations

- Spring stiffness: $K = m(2 \times \pi \times f)^2 = 789.56 \{N/m\}$ approx. = 790 {N/m}
- Peak force: $F_{\text{peak}} = K \times x = 63.2 \{N\}$
- Torque at pinion shaft: $T = Fr = 1.27 \{N/m\}$
- Energy per stroke: $E = \frac{1}{2} Kx^2 = 2.528 \{J\}$
- Usable energy per cycle: $E_{\text{cycle}} = 5.056 \{J\}$
- Average electrical power: $P = 7.07 \{W\}$
- Rated voltage: 12 – 24 V
- Recommended power rating: 25 – 28V

Battery & Converter

- Battery: 12 V, 2 – 5 Ah
- Bidirectional DC–DC converter: 10 – 20 W, 12 – 24 V input range

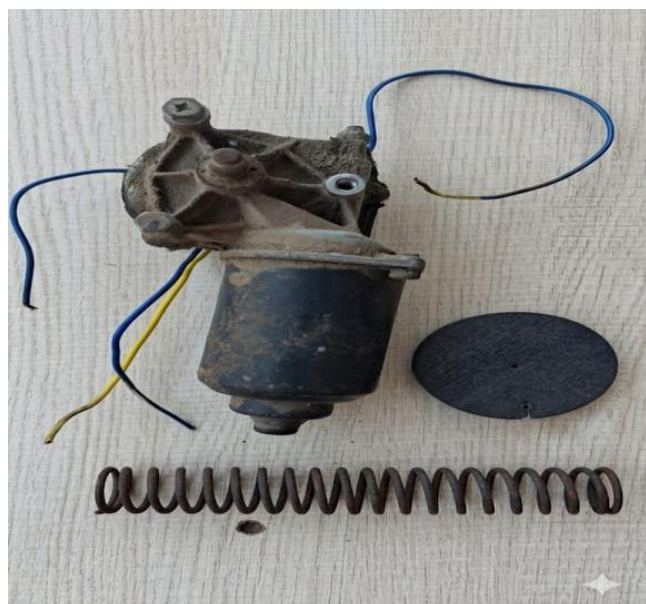


Figure 3: Wiper motor, Coil spring & Cam

Table 2

Parameter	Symbol	Value	Unit
Mass	m	5	kg
Frequency	f	2	Hz
Spring Stiffness	k	790	N/m
Displacement	x	0.08	m
Force	F	63.2	N
Pinion Radius	r	0.02	m
Torque	T	1.264	N-m
Angular Velocity	ω	6.283	rad/s
Mechanical Power	P _m	10.1	W
Electrical Power	P	7.07	W

V. RESULTS AND DISCUSSION

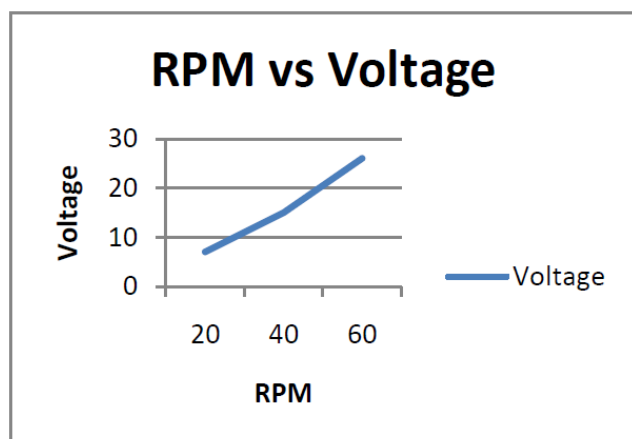


Figure 4

The fabricated regenerative suspension system was experimentally tested under simulated vibration conditions to evaluate its capability of converting mechanical vibration energy into electrical energy. The performance of the system was analyzed by measuring voltage generation at different rotational speeds and vibration frequencies.

The obtained experimental results demonstrate that the proposed system successfully converts suspension vibrations into useful electrical energy using the rack and pinion mechanism coupled with a DC generator

5.1 Voltage Variation with RPM

The output voltage generated by the system was measured at different generator rotational speeds. It was observed that the generated voltage increases with increase in RPM due to higher rotational motion of the generator shaft.

At low rotational speed, the generated voltage was comparatively small. As the RPM increased, higher electrical output was obtained. The maximum voltage recorded during experimentation was approximately 26 V at 60 RPM.

The relationship between RPM and output voltage is shown in Figure 4.

5.2 Voltage Variation with Frequency

The regenerative suspension system was tested under different vibration frequencies to analyze its performance under varying operating conditions. Experimental observations indicate that higher vibration frequencies result in greater suspension movement, leading to increased generator rotation and voltage output.

The system showed effective performance within the practical vibration frequency range of 1 Hz to 2 Hz, which corresponds to normal and moderately rough vehicle operating conditions.

5.3 Power Output Comparison

Conventional suspension systems dissipate vibration energy completely in the form of heat without energy recovery. The proposed regenerative suspension system successfully converts a portion of this wasted energy into electrical energy.

The developed prototype generated approximately 7 W of electrical power under maximum operating conditions. This power output is sufficient for low-power automotive applications such as LEDs, sensors, and battery charging support systems.

5.4 Advantages of Proposed System

The proposed regenerative suspension system offers several advantages:

- Simple and compact design
- Low manufacturing cost
- Easy fabrication and maintenance
- Effective conversion of vibration energy into electrical energy
- Suitable for electric and hybrid vehicles
- Improves overall energy efficiency
- Environmentally friendly energy harvesting approach

Table 3: Cost Estimation of Prototype

Sr. No.	Item	Quantity	Estimated Cost (₹)
1	DC Motor / Generator	1	2000
2	12V LiFePO ₄ Battery	1	1500
3	Rack & Pinion Set	1	1500
4	Pinion (separate)	1	400
5	Spring	1	1000
6	Bearings	2	400 (200 each)
7	Frame Material & Fabrication	—	1800
8	Fasteners / Wiring	—	1000
—	Total Estimated Cost		₹ 9300/- (Approx.)

VI. CONCLUSION

The present work successfully demonstrates the design, fabrication, and testing of a rack and pinion based regenerative suspension system capable of converting vibration energy into useful electrical energy.

The developed system effectively converts the vertical motion generated due to suspension vibrations into rotational motion using a rack and pinion mechanism. The rotational motion drives a DC generator for electricity generation.

Experimental testing of the fabricated prototype showed that the generated output voltage varies from 7 V to 26 V depending on vibration intensity and generator speed. The maximum generator speed recorded during experimentation was 60 RPM, producing approximately 7 W of electrical power output.

The obtained results validate the feasibility of energy harvesting from vehicle suspension systems. The proposed mechanism is simple, compact, economical, and suitable for implementation in modern automobiles, especially electric and hybrid vehicles where efficient energy utilization is important.

The project demonstrates a sustainable approach toward reducing energy wastage in automotive systems and improving overall vehicle energy efficiency.

VII. FUTURE SCOPE

Although the developed regenerative suspension system successfully demonstrates vibration energy harvesting, several improvements can be implemented in future work to enhance system performance and practical applicability.

1. Advanced Generator Integration: Higher efficiency generators can be used to improve electrical power generation and reduce mechanical losses.

2. Energy Storage System: The generated electrical energy can be stored in rechargeable batteries or super capacitors for practical utilization.

3. Smart Monitoring and Control: Sensors and microcontrollers can be integrated for intelligent monitoring and control of energy generation.

4. Real Vehicle Implementation: The developed system can be integrated into actual vehicles for real-time testing and performance evaluation under practical operating conditions.

VIII. APPLICATIONS

The regenerative suspension system has wide range of applications which are as follows:

- Electric Vehicles
- Hybrid Vehicles
- Heavy Commercial Vehicles
- Smart Transportation Systems
- Energy Efficient Automotive Systems
- Suspension Testing Laboratories
- Low Power Energy Harvesting Devices
- Automotive Research and Development

IX. ADVANTAGES

The major advantages of the proposed regenerative suspension system are as follows:

- Simple and compact construction
- Low manufacturing and maintenance cost
- Effective vibration energy harvesting
- Environmentally friendly system
- Improves overall vehicle efficiency
- Suitable for prototype and practical applications
- Can support low-power electrical devices
- Reduces energy wastage in suspension systems

X. LIMITATIONS

The developed system also has certain limitations which can be improved in future work:

- Lower efficiency at small vibration amplitudes
- Limited power generation under low RPM conditions
- Manual testing instead of actual vehicle testing
- Mechanical friction losses in rack and pinion mechanism
- Limited energy storage capability in present prototype

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