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An experimental investigation of an energy regeneration suspension

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Abstract

Energy absorbed from road bumps in traditional suspensions is dissipated as heat. An energy regeneration suspension (ERS) has the capability to capture and store this energy in batteries. It has the potential to be used in several categories of vehicles, encompassing cars, trucks, buses, and even trains. ERS technology shows significant promise in enhancing the fuel efficiency and environmental sustainability of vehicles. In this paper, the design of an ERS that converts kinetic energy into electrical energy is presented. The primary objective is to identify key design parameters that result in high magnetic intensity levels in the air gap of the ERS model. Optimizing these parameters is essential to maximize the advantages of ERS while minimizing any drawbacks. The study investigates the impact of different magnetic permeability materials in the ERS model using ANSYS software. A test rig is established based on the analysis results to assess the energy regeneration efficiency of the ERS model under various excitations. Experimental results demonstrate that ERS models with higher permeability inner sleeves exhibit superior energy regeneration efficiency.

Keywords: energy regeneration; regenerative suspension; vehicle efficiency; suspension energy harvesting.

I. Introduction

Vibrations in mechanical systems significantly impact equipment stability and safety. Addressing vibration issues involves modifying mechanical structures and designing customized control systems for the specific vibration system. Mitigating vibration can be achieved through structural adjustments and tailored control strategies. Utilizing energy recovery processes can also serve as an effective mitigation strategy for vibration, enabling the collection and storage of energy while reducing the impact of vibrations on mechanical systems. The energy recovery processes for vibration can be classified into three main categories: rotational, linear, and material-based. Among these, the linear energy regeneration mechanism stands out for its high efficiency, non-contact operation, not requiring lubrication, and absence of environmental pollution. This mechanism uses a series of circuits to enable the effective collection and storage of energy in a battery.

The suspension system is a vital component in vehicles, ensuring smooth and stable operation, directly influencing driving comfort, operational stability, and safety. Vehicles equipped with energy-recovering suspensions improve efficiency by capturing and storing kinetic energy lost during suspension movements. Particularly beneficial for electric vehicles, energy recovery suspensions offer an innovative solution to increase driving range by harnessing wasted

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energy from vibrations to recharge the vehicle's battery. This technology transforms mechanical energy, typically dissipated as heat by the shock absorber, into electrical energy for direct battery charging [1]. The conversion of mechanical energy produced by vibrations into electrical energy is achieved by employing a linear generator within the system. Various designs of the ERS, such as the novel semi-active energy regenerative suspension system, integrate an adjustable shock absorber and a linear motor to optimize the cost and power rating of the actuator simultaneously [2].

During road travel, passive suspension systems absorb the majority of road vibrations to enhance passenger comfort. An alternative to the passive suspension is the electric suspension system that utilizes an electromechanical integration of a permanent magnet DC brushless motor and a ball screw [3]. Experimental results have validated the efficacy of the electric suspension system model, demonstrating the prototype actuator's ability to efficiently dampen shocks caused by low-frequency road vibrations. Although regenerative energy capacity is limited, electric suspension presents a viable alternative to active suspension and addresses the issue of high energy consumption.

David and Bobrovsky [4] introduced an innovative hybrid vehicle suspension topology that combines active damping features with energy regeneration capabilities. When subjected to Gaussian noise, the semi-active mode can recover approximately 60 % of the power regenerated in the passive mode. This mode effectively serves a dual purpose by recuperating a significant amount of power (30 % of the maximum potential of passive mode) while improving body isolation. Zou *et al.* [5] unveiled a revolutionary hydraulic energy regenerative shock absorber (HERSA) derived from the conventional telescopic shock absorber. Liu *et al.* [6] proposed an electromagnetic energy regenerative suspension for energy harvesting and active control. They designed a PID controller utilizing the BP neural network algorithm and analyzed the dynamic performance of the vehicle. Liu *et al.* [7] conducted simulations and experiments to demonstrate significant improvements in vehicle dynamic performance across various scenarios of different road surfaces and vehicle speeds. The energy regenerative suspension displayed the capability to capture vibration energy, achieving a self-sustaining energy efficiency of approximately 55 % and an energy regeneration efficiency of around 16 %.

A controllable shock absorber equipped with an energy regeneration mechanism was proposed for a quarter car suspension model to reduce undesired vibrations [8]. Experimental confirmation showed that the generator can produce adequate voltage to achieve satisfactory damping forces. Yang *et al.* [9] explored the design complexities of an energy regeneration circuit in a hybrid vehicle setup, focusing on suspension performance and energy regeneration efficiency. They introduced a hybrid suspension system, developed a dynamic model based on a quarter car model, and validated the simulation results through bench tests. A comparison between the performance of the hybrid suspension and the original suspension was conducted using simulations, revealing a significant improvement in energy recovery and regeneration efficiency with the new design.

Wei *et al.* [10] proposed an electromagnetic actuator for energy regeneration and vibration control, consisting of specific components such as three soft iron rings, three coils, three springs, and four permanent magnetic rings. Experiments conducted with different frequencies and amplitudes demonstrated effective suppression of controlled object vibrations within 5.5 % and an electromotive force to input amplitude ratio of 0.13, showcasing the actuator's efficiency in vibration suppression and energy regeneration. Dai *et al.* [11] detailed the design process of a linear electromagnetic actuator energy-reclaiming device, utilizing optimization techniques to improve its electromagnetic characteristics. Lv *et al.* [12] provided a systematic and comprehensive review of hydraulically-driven vehicle suspension and their potential for energy recovery, emphasizing the importance of these suspension types in the context of vehicle energy recovery. Over the years, many researchers have reviewed and investigated different facets of energy regenerative suspension. For instance, Zhang *et al.* [13] developed a new energy regenerative damper with dual overrunning clutches for electric vehicles, focusing on optimal performance and driving comfort. In another study, Shi *et al.* [14] presented the control design and fuel efficiency of power split hybrid electric vehicles with energy regeneration suspension. Morstyn *et al.* [15] investigated the capacity of using gravity energy storage in abandoned deep mine shafts. He *et al.* [16] described the applicability of energy regenerative techniques including hydraulic vehicles, construction machinery, wave energy converters, and regenerative suspensions. Huang *et al.* [17] presented a mathematical model for the motor component of an electromagnetic suspension. Sabzehgar *et al.* [18] proposed a new energy regenerative suspension mechanism that combines a mass-spring unit, a boost charger, and a rotary generator. Fu *et al.* [19] provided a systematic review of energy regenerative suspensions and their optimization methods and control strategies. Long *et al.* [20] introduced a dual actuator regenerative suspension for motor-based driven electric vehicles. Meng *et al.* [21] presented research on the control of vehicle electromagnetic suspension. Jiang *et al.* [22] conducted simulations to improve the vibration suppression of suspension vehicles. Liu *et al.* [23] proposed a hydraulic interconnected suspension with energy recovery (EHA-HIS) that simultaneously enhances riding comfort and road-holding ability while converting vibration energy into usable electrical energy. Finally, Qi *et al.* [24] comprehensively reviewed "mechanical motion rectification-based electromagnetic vibration energy harvesting (MMR-based EMVEH)" to address the challenge of wasted energy from vibrations. This technology offers a promising solution by converting vibrations into usable electrical power.

The performance of ERS systems relies heavily on the dynamics of the vehicle's suspension system. This dependence stems from the ERS's operation of capturing kinetic energy produced during suspension movement and converting it into electrical energy. The effectiveness of this energy conversion process is greatly influenced by the response frequency of the suspension, particularly concerning the resonance phenomena. Resonance occurs when the suspension operates at its resonant frequency, resulting in maximum vibration amplitude for a given input force. This characteristic can be advantageous for ERS, as it facilitates a more substantial transfer of energy from the suspension's motion to the energy harvester. By strategically configuring the ERS to operate close to the suspension's resonant frequency, it becomes possible to capture a larger quantity of energy.

This study seeks to address a gap in existing energy regeneration suspension (ERS) technology. While prior studies have concentrated on ERS concepts through simulations, real-world testing remains limited. Moreover, these studies have mainly centered on conventional suspension designs, which might not be ideal for maximizing energy capture. This article presents an experimental investigation of a novel ERS system that integrates a hydraulic suspension with an energy regenerator. This case study marks the initial phase of technology development, showcasing the growing research focus in developing nations on creating viable and efficient ERS solutions for future vehicle productions.

The paper is organized as follows: Section II introduces the ERS model, followed by Section III which discusses the fundamental design parameters relevant to the ERS model, the magnetic field analysis pertaining to the ERS model, and results and discussions. Finally, the conclusion summarizing the findings and insights of the study is given in Section IV.

II. Materials and Methods

A. Energy regeneration suspension (ERS) model

The energy regeneration suspension model expands upon the established quarter car concept by integrating additional components that are specifically designed to capture energy produced by suspension movements. The updated model contains additional components such as generators and energy storage systems to explore the potential conversion of lost energy from bumps into usable electricity. While the quarter car model aims to understand the fundamental suspension characteristics, the energy regeneration model investigates this behavior for energy harvesting. An energy regeneration suspension model enables the analysis and simulation of the behavior of a suspension system that absorbs and transforms the energy expended during bumps into electrical energy. Through the examination of this model, engineers can optimize design parameters to maximize energy capture efficiency, improve ride comfort, and enhance overall vehicle performance. The energy regeneration suspension system consists of two main components, as illustrated in Figure 1. The first component is a hydraulic suspension that effectively isolates vibrations originating from the road, ensuring a comfortable riding experience. The second component is an energy regenerator, responsible for capturing the kinetic energy generated by these vibrations and subsequently converting it into electrical energy. Finally, the generated electrical energy is stored in a battery for later use within the vehicle.

The energy regenerator comprises a magnet array and a coil array. The magnet array consists of ring-shaped permanent magnets arranged in such a way that similar poles of adjacent magnets are oriented toward each other. This arrangement causes the magnetic flux to be redirected in the radial direction around the outer sleeve. Ring-shaped spacers are positioned between the magnets to maintain the arrangement and spacing.

To attain a strong and efficient magnetic field within the coil, it is important to carefully consider the choice of material for the inner sleeve. This material choice significantly influences the direction and concentration of the magnetic flux. The use of material with high magnetic permeability results in a substantial improvement in the inner sleeve's ability to conduct

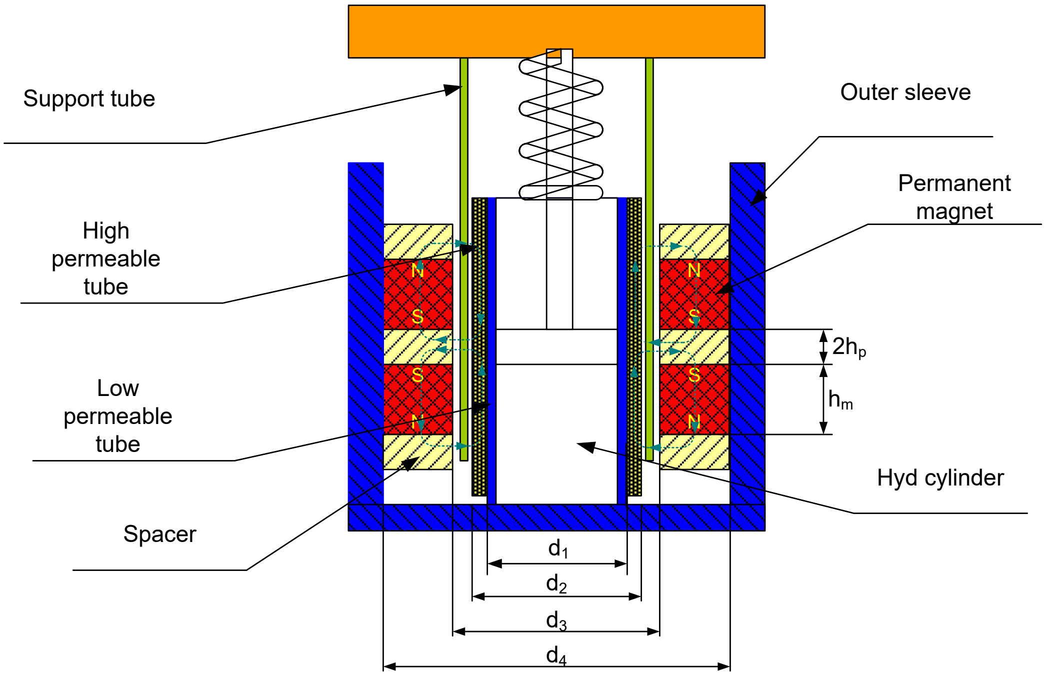


Figure 1. Mechanical structure of ERS.

magnetic fields. This translates to an increased concentration of magnetic flux density within the coil. Consequently, the overall reluctance of the magnetic loop is minimized. Reluctance refers to the resistance experienced by the magnetic flux as it flows through the circuit. Lower reluctance signifies a more efficient path for the magnetic flux, leading to a stronger magnetic field and improved overall performance of the system.

The coil assembly comprises multiple coil windings and a support tube. The support tube moves in response to vibrations in the suspension, thereby inducing relative motion with the magnetic field. Thus, the support tube is made from a material with large electrical resistance to eliminate eddy current losses in the tube.

The coil array is a crucial component inside the energy regeneration suspension system as it enables the conversion of kinetic energy into electrical energy. This assembly of coils moves back and forth along the axial direction, or the centerline, of a component called the gen-shock. The gen-shock itself is situated within a magnetic field. The motion of the coils within the magnetic field induces the flow of electrical energy. To quantify the electrical energy generated, it is necessary to measure the regenerated voltage across each coil. This calculation, as specified in equation (1), considers factors such as the magnetic field strength, the velocity of the coil movement, and the number of turns within each coil. Understanding the relationship between these elements and the resulting voltage allows for optimizing the design of the coil array and the gen-shock to maximize the energy captured from the suspension movement.

$$V = \int_0^L v_z B_r \, dl = v_z B_{ave} L \quad (1)$$

where B_r is the radial magnetic field intensity, B_{ave} is the average of radial magnetic field intensity at the coil center and depends on the coil position, L is the coil's length and v_z is the relative velocity of the coil conductor.

B. Equations and mathematical expressions

1) Diameter of permanent magnetic pole

The magnetic flux Φ passing through the upper permanent magnet is presented in equation (2),

$$\Phi = B_m \frac{d_4^2 - d_3^2}{4\pi} \quad (2)$$

where d_3 and d_4 are inside diameters of the permanent magnet (or spacer) and outer sleeve, respectively.

The magnetic flux density B_s passing through on the highly magnetically permeable spacer wall is presented in equation (3),

$$B_s = \frac{\Phi}{S_s} = \frac{B_m \pi (d_4^2 - d_3^2)}{4\pi d_3 h_p} = \frac{B_m (d_4^2 - d_3^2)}{4 d_3 h_p} \quad (3)$$

where $2h_p$ is a clearance of two permanent magnets.

The diameter of the magnetic pole must be properly selected using equation (4) to ensure that the magnetic flux density passing through the permanent magnetic top is equal to that emitted from the side of the spacer $B_s = B_m$

$$d_4^2 - d_3^2 = 4 d_3 h_p \quad (4)$$

2) Determination of the air gap

A magnetic insulation material is installed between the hydraulic cylinder and the permanent magnetic pole to prevent the magnetic permeability phenomenon in the hydraulic cylinder. The permanent magnet volume, V_m is calculated as in equation (5)

$$V_m = \frac{\pi(d_4^2 - d_3^2)}{4} h_m = \pi d_3 h_p h_m \quad (5)$$

where h_m is the height or the length of the permanent magnet.

The air gap volume V_{ag} is calculated using equation (6)

$$V_{ag} = \frac{\pi(d_3^2 - d_2^2)}{4} h_p \quad (6)$$

The highest magnetic energy density is attained when the distance between the poles and the air gap below them is approximately equal to the strength of the permanent magnetic field, as shown in equation (7)

$$V_m = 2V_{ag}$$

or

$$d_2 = \sqrt{(d_3^2 - 2d_3 h_m)} \quad (7)$$

where d_2 is the outside diameter of the high permeable tube.

The magnetic flux passing through the armature is assumed to be equal to the magnetic flux passing through the gap between the poles, as shown in equation (8)

$$\pi B_{sw} d_3 h_p = \pi B_{ar} d_2 h_a \quad (8)$$

where h_a is the armature wall length using equation (9), B_{ar} is the armature magnetic flux density.

$$h_a = \frac{B_{sw} d_3 h_p}{B_{ar} d_2} \quad (9)$$

The external diameter of the armature is calculated as shown in equation (10)

$$d_1 = d_2 - 2h_a \quad (10)$$

where d_1 is the outside diameter of the low permeable tube.

III. Results and Discussions

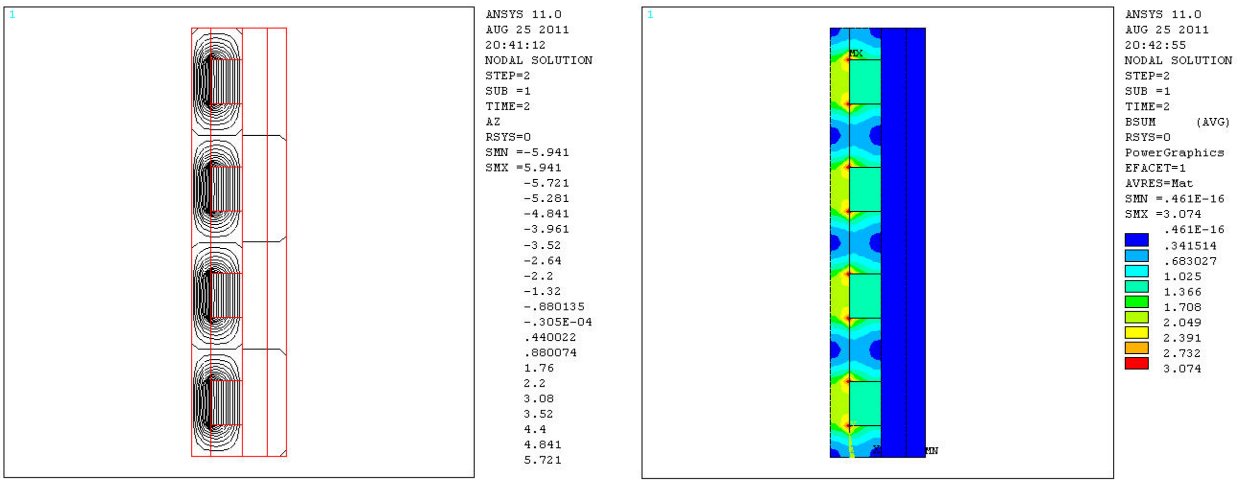
A. Magnetic field analysis in ERS model

The magnetic material utilised in this study is Nd-Fe-B Grade 50, produced by Ningbo Ketian Magnet Company. This magnetic material exhibits several notable characteristics, such as a linear demagnetization curve, a low temperature dependence, a high remanent flux density, a strong coercive force, and a high energy product. The specifications of the magnet are:

- Remanent magnetic flux density (B_r) = 1.2 Tesla (T)
- Coercive force (Hc) = 900 kiloampere per meter (kA/m)
- Operating temperature = 20 degrees Celsius (°C)

The magnetic flux and density distribution simulation results were obtained from analysis using ANSYS software. In this section, the influence of different materials on the magnetic flux density distribution is considered for two cases, as follows:

Case 1: The outer and inner sleeves are made of high permeability materials such as 1080 steel (μ=875×10^{-6} Hm^{-1}). The results are shown in Figure 2. The analysis of the magnetic field distribution reveals an unexpected outcome. The simulation results revealed that the magnetic flux density (1.946 T) is predominantly concentrated within the outer sleeve, even though both the inner and outer sleeves possess identical permeability. This occurrence can be attributed to



(a) (b)

Figure 2. Simulation results of Case 1 showing (a) magnetic flux and (b) magnetic flux density distribution.

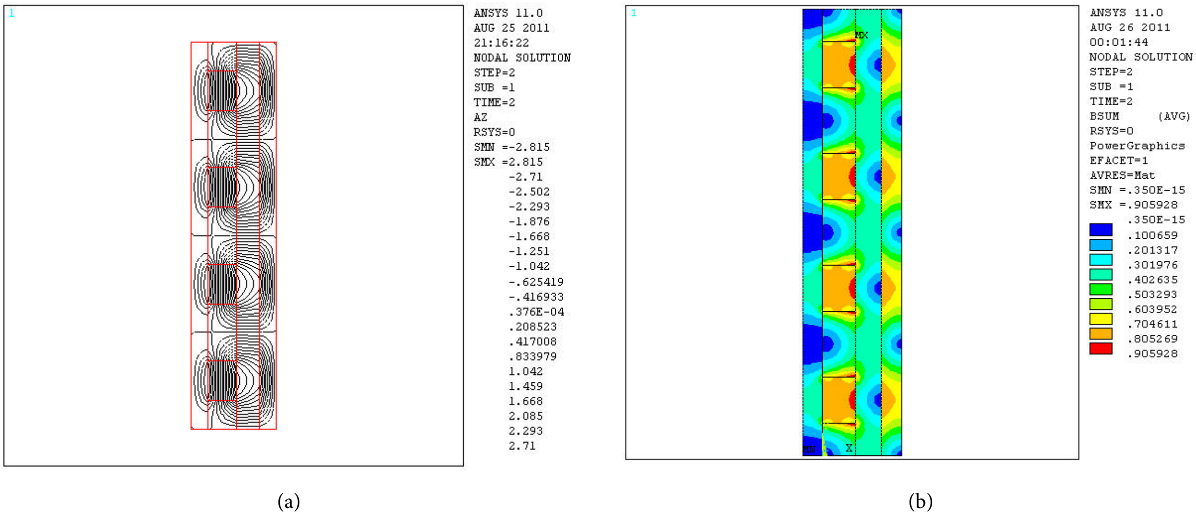


Figure 3. Simulation results of Case 2 showing (a) magnetic flux and (b) magnetic flux density distribution.

magnetic flux leakage, where the magnetic field favors a path of lower reluctance, with the air gaps offering less resistance than the inner cavity of the gen-shock. Consequently, the magnetic flux bypasses the inner sleeve containing the copper coil. This lack of interaction between the magnetic field and the coil results in a diminished magnetic flux magnitude passing through the copper coil. Unfortunately, this leads to a decrease in the efficiency of the energy regeneration. The system's capacity to fully harness the kinetic energy is compromised by the constrained magnetic flux interaction with the coils. It is crucial to optimize the design of the gen-shock and to explore alternative configurations to improve the coupling between the magnetic field and the copper coil for maximized energy conversion.

Case 2: The outer sleeve is made of low permeability materials such as aluminum (μ=1.27×10^{-6} Hm^{-1}). Meanwhile, the material of the inner sleeve has high permeability such as 1080 steel (μ=875×10^{-6} Hm^{-1}). The result is shown in Figure 3.

The implemented design improvement appears to have successfully addressed the issue of magnetic flux leakage. In contrast to Case 1, there has been a significant increase of 0.48 T in the magnetic flux density passing through the copper coil. This rise signifies an increase in magnetic field concentration within the coil, a critical factor for achieving optimal energy conversion. However, these improvements come with certain drawbacks. There is a noticeable reduction in the magnetic flux density within the outer sleeve, dropping from 1.946 T to 0.35 T. While this decrease may appear unfavorable, it indicates successful redirection of the magnetic flux towards its intended destination, namely the copper coil.The optimization of the energy regeneration suspension system requires a careful balance between the flux density of the outer sleeve and that of the coil. By strategically manipulating the magnetic field distribution, engineers can maximize the amount of magnetic flux interacting with the coils, ultimately resulting in a significant improvement in overall energy capture efficiency.

B. Magnetic field analysis in ERS model

A test rig, shown in Figure 4, is constructed to investigate the output voltage and energy recovery efficiency of the ERS. In this setup, a pneumatic cylinder serves as the excitation source. Two laser

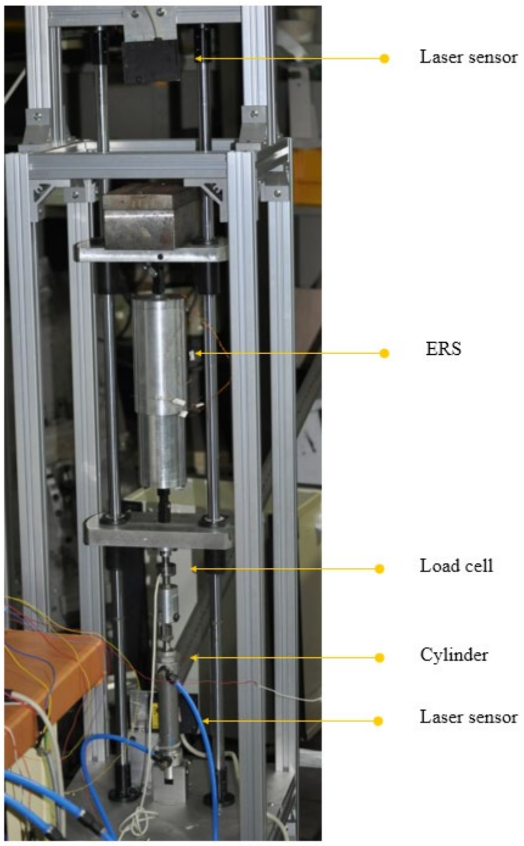


Figure 4. Test rig.

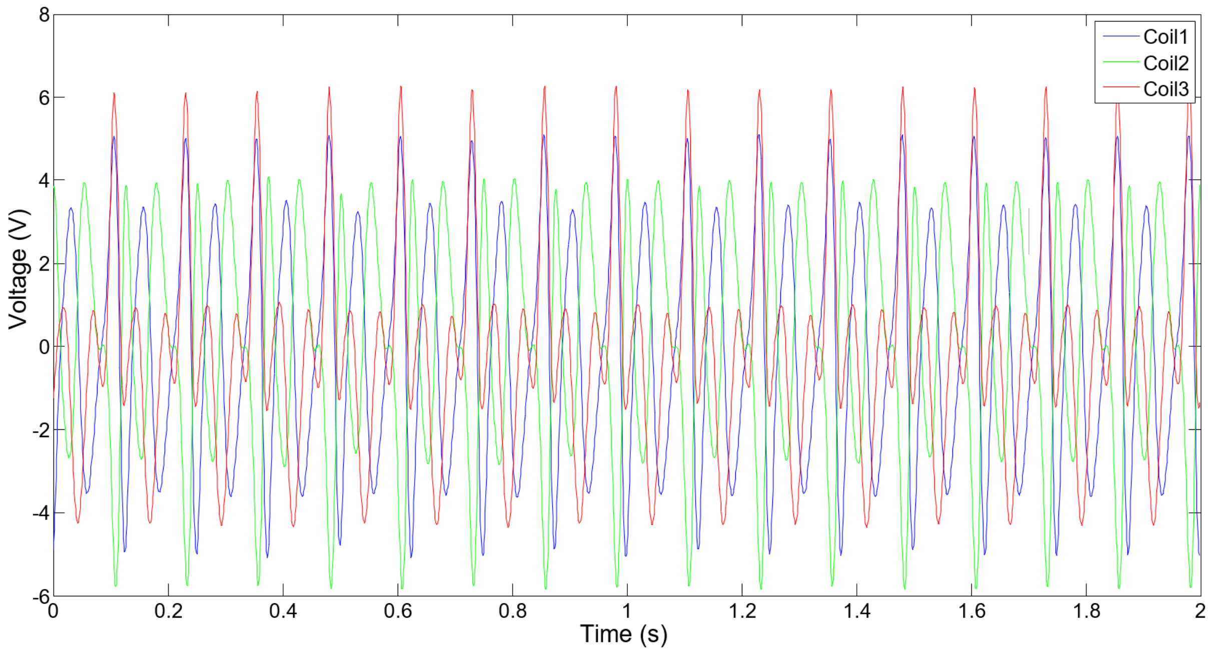


Figure 5. Time history of regenerated voltage for each coil at various excitation frequencies.

sensors are incorporated to monitor the vertical displacement of the mass and the base, while a load cell is used to measure the force produced by the exciter. The system utilizes an Advantech PCI 1711 card as the I/O interface to extract the output signals from the displacement sensor and generate the output signals to regulate the proportional valve. Additionally, a personal computer (PC) manages all the I/O data operations throughout the system.

1) Time response of regenerated voltage under sinusoidal signal

Modification to the current setup was proposed to account for real-world road irregularities that affect harvested power (voltage, current). This involved programming the hydraulic system with actual road data to replicate the random vibrations experienced by a vehicle suspension on diverse road surfaces, improving the experiment's practical relevance. The applied excitation is a sinusoidal signal with an amplitude of 10 mm [25][26][27] and a frequency of 8 Hz [28][29]. The resulting voltage waveform is shown in Figure 5, where the solid line represents Coil 1, the dotted line represents Coil 2, and the dashed line represents the voltage generated by Coil 3. Based on the experimental results, it is evident that Coils 1 and 3 exhibit identical phases, but Coil 2 demonstrates a distinct phase difference. It is apparent as the magnetic field at the equilibrium position of Coil 1 and is inversely oriented to that of Coil 2. Furthermore, the frequency of the regenerated voltage aligns with the excitation.

2) Effect of coil position in the magnetic distributive field

This subsection explores the critical relationship between the coil's equilibrium position and the efficiency of energy regeneration. As the previous analysis has established, the intensity of the magnetic field exhibits a clear and identifiable pattern. The maximum value is observed at the central region of the spacer, which is the non-magnetic element that separates the permanent magnets. On the other hand, the intensity decreases to its minimum value precisely at the midpoint of each permanent magnet segment. The experimental results depicted in Figure 6 provide proof that the regenerated voltage output by the coils is directly influenced by the variation in magnetic intensity. It can be observed that the regenerated voltage reaches its maximum value when the equilibrium position is at the center of the spacer (Position 1), as indicated by the dashed line. The equilibrium position of the coil is the center of the magnetic (Position 3) the voltage represented by a dotted line. The solid line represents the regenerated voltage at any position of the coil (Position 2). This highlights the importance of precisely controlling the coil's equilibrium position within the gen-shock assembly. Thus, the energy regeneration process can be optimized and the captured electrical energy output from the suspension system's movement can be maximized by strategically placing the coils in the region of strongest magnetic intensity.

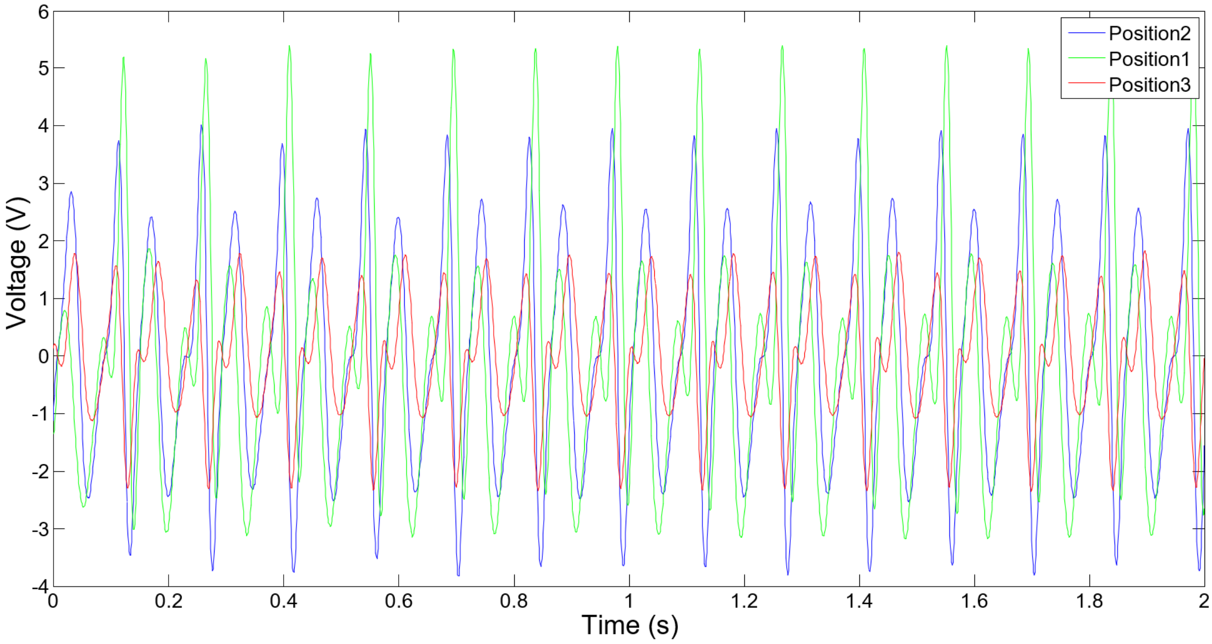


Figure 6. Comparison of regenerated voltage with difference equilibrium position for excitation frequency 7 Hz.

3) Effect of different magnetic permeability materials

Apart from the coil's placement within the magnetic field, the choice of material for the inner sleeve is also an important factor in the effectiveness of energy regeneration. As illustrated in Figure 2, if the inner sleeve is constructed from aluminum, a material with low magnetic permeability, the magnetic flux traversing the air gap between the inner sleeve and the coil remains minimal. This limited interaction between the magnetic field and the coil results in a low regenerated voltage, as illustrated by the blue line in Figure 7.

In contrast, the use of high permeability material such as steel for the inner sleeve, as shown in Figure 3, results in a notable increase in magnetic intensity within the air gap. The observed phenomena can be attributed to the capacity of high-permeability materials to concentrate and direct magnetic flux lines. This enhanced magnetic field interaction with the coil results in higher regenerated voltage, as shown by the red line in Figure 7. The experimental results clearly demonstrate the direct relationship between the permeability of the inner sleeve material and the voltage generated. Thus, the system's ability to convert kinetic energy from suspension movement into

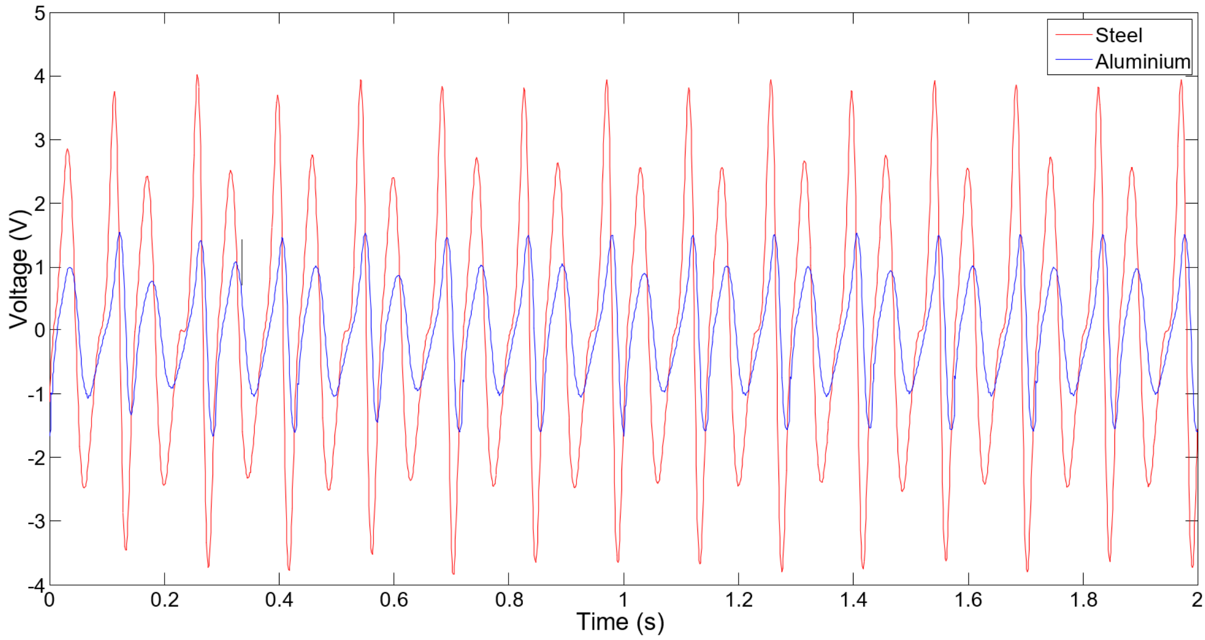


Figure 7. Regenerated voltage versus time.

electrical energy can be maximised by correctly selecting a material with high permeability for the inner sleeve that can effectively channel the magnetic field towards the coil.

4) Regenerated power

The previous analysis revealed an intriguing phenomenon: the voltages produced in Coil 1 and Coil 3 have the same phases, yet the phase of Coil 2 differs by approximately 180 degrees. To capitalize on this phase difference and maximize energy output, a specific electrical circuit configuration is implemented, as depicted in Figure 8. The design incorporates a strategic connection between the end point of coil 1 to the starting point of coil 3. This creates a series connection of these two coils, effectively summing their voltages. Meanwhile, the two endpoints of Coil 2 are directly connected, essentially shorting them. Then, the starting points of both Coil 1 and Coil 2 are connected to opposing ends of a bridge circuit. The remaining two open ends of the bridge circuit are then bridged by an external resistor with a resistance of 50 ohms. This resistor functions as the load for the generated electricity. This circuit configuration leverages the phase difference between the coils. Since Coils 1 and 3 are in phase, their voltages add constructively to the series connection, resulting in a stronger combined voltage across the bridge circuit. Conversely, the shorted connection of Coil 2 effectively nullifies its voltage contribution, hence preventing it from opposing the combined voltage from the other two coils. By exploiting this phase relationship and strategically connecting the coils, the circuit design aims to maximize the total voltage output delivered to the external resistor, ultimately resulting in a more efficient energy harvesting process from the suspension system.

Figure 9 presents the comparison of the voltage between two ends of the resistor when using an inner sleeve with different magnetic permeability materials. The excitation signal used in this experiment exhibits a sinusoidal waveform with an amplitude of 10 mm and a frequency of 6 Hz. Furthermore, it is observed that the

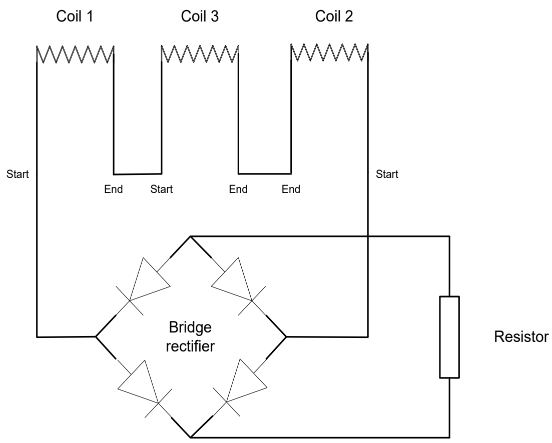


Figure 8. Bridge rectifier circuit.

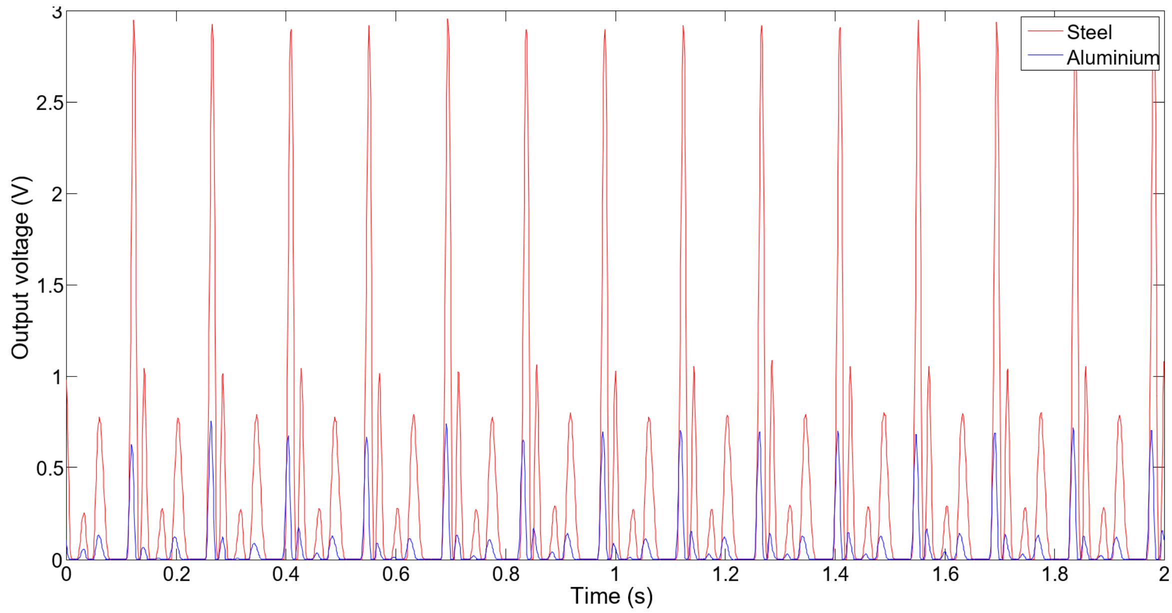


Figure 9. Comparison of rectified voltage for two various magnetic permeability materials.

output power of an ERS with a steel inner sleeve shown by the red line surpasses that of the ERS with an aluminum inner sleeve shown by the blue line. The energy regeneration efficiency of ERS is about 42.34 % for the inner steel sleeve and 9.06 % for the inner aluminum sleeve.

IV. Conclusion

Energy regeneration suspension (ERS) systems can play a significant role in facilitating the sustainable development of vehicles that are both fuel-efficient and environmentally friendly. This study has successfully identified the essential design parameters that would maximize the magnetic flux density throughout the coil in an ERS. The impact of different magnetic permeability of materials was analyzed using Ansys software. The findings from the analysis indicate that the combination of a low permeability outer sleeve and a high permeability inner sleeve results in the concentration of the magnetic field, hence enhancing the efficiency of energy regeneration. Experimental validation has verified that the regenerated voltage is influenced by both the position of the coil and inner sleeve material, with surprisingly higher efficiency achieved using a low-permeability aluminum inner sleeve compared to high-permeability steel. These findings provide valuable insights for optimizing ERS design and pave the way for more efficient conversion of suspension movement into usable electrical energy. This current work has mostly concentrated on the electromagnetic design of the harvester. However, to fully assess the efficacy of the proposed ERS system, it is essential to consider both the mechanical aspects of the suspension as well as the electromagnetic characteristics of the energy harvester. Future work can expand the analysis to include characterization of the suspension's frequency response and to investigate design optimizations that provide a more optimal alignment between the vibration frequencies of the suspension and the operational range of the harvester. Furthermore, it is important to recognize the intricate relationship between mechanics and electromagnetics in the ERS design. To fully optimize the energy harvesting process, future studies should incorporate a more extensive analysis that considers both the mechanical dynamics of the suspension system and the electromagnetic characteristics of the energy harvester. The implementation of this co-design approach will facilitate the customization of the ERS to effectively resonate with the suspension movements, maximizing the conversion of mechanical vibration energy into usable electrical power.

Declarations

Author contribution

N.H. Tho and L.T. Danh contributed equally as the main contributors of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Additional information

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