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MODELING AND CHARACTERIZATION OF A REGENERATIVE SHOCK ABSORBER FOR IMPROVED VEHICLE EFFICIENCY

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Abstract: *This paper proposes the development of an innovative model of a regenerative shock absorber, capable of transforming the kinetic energy dissipated during the operation of the suspension into an additional source of electrical energy. The system is based on a classic hydraulic shock absorber, modified by integrating an energy conversion module, which uses the internal oil pressure to drive a hydraulic mill-type mechanism. This generates rotary motion transmitted to an electric micro-generator, connected to the vehicle's storage system. The modelling and functional analysis of the system are performed in the Simulink environment, where the dynamics of the entire assembly in real operating conditions are simulated.*

Key words: *active regenerative suspension, electromechanical system, energy analysis, regenerative shock absorber, passive recovery.*

1. Introduction

Shock absorbers play a major role in car suspension systems, reducing road vibrations that reach the chassis and passengers. The automotive industry is facing accelerated changes due to climate change, resource depletion and the increasing demand for green mobility solutions, thus moving towards energy-efficient and less polluting propulsion systems [2], [10]. The transition to sustainable mobility largely depends on hybrid and electric vehicles, which offer alternatives to traditional internal combustion engine vehicles. The main obstacle to maximizing energy autonomy and energy conversion efficiency exists in systems where all potential sources of energy recovery are required. Energy regeneration technologies serve as essential components that enhance the established functions of both regenerative braking systems and integrated solar panels [1], [7]. This sector is full of potential, but shock absorbers have undergone relatively

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little research compared to other regeneration-related systems. As the name suggests, shock absorbers are meant to hold the passengers in comfort and maintain vehicle stability. In doing so, they dissipate kinetic energy as heat while driving on uneven roads or braking. The energy that otherwise disperses away can be harnessed by technologies that convert dissipated mechanical energy into marginal electric energy that can be stored and reused [6], [11]. A regenerative shock absorber stands for this main idea, converting kinetic energy generated during suspension oscillations into an additional source of electrical energy.

Incorporating a regenerative mechanism means creating avenues either electromechanically or piezoelectrically within the shock absorbers. The relative movement between the wheel and the chassis is then converted into electrical current by such mechanisms. This energy can then be supplied to the traction batteries of hybrid and electric vehicles to assist in the charging process independent of an external power source. Depending on the system configuration and driving conditions, studies have shown that such devices can recover between 100 and 400 W per shock absorber, which represents a significant contribution to the vehicle's energy needs, especially in urban conditions, where bumps and frequent stops are common [4], [8].

Besides offering extra battery charge power, these systems also have other benefits. For instance, regenerative absorbers of vibrations include the opportunity to reduce the fuel consumption (for hybrid vehicles), thus indirectly reducing CO_2 emissions [3], [12]. Also, for electric vehicles, the increased autonomy between two charging cycles raises their commercial appeal and helps to fight one of the most common criticisms of this propulsion: limited autonomy [5], [9].

The present work aims to create and analyze a working model of a regenerative shock absorber capable of converting mechanical energy absorbed by the suspension during its operation into usable electrical energy. This project involves both physical and kinematic system modeling, as well as the simulation and validation of its performances through numerical analysis tools. The study made by Marco, M et al. shall assess possible types of energy conversion (electromagnetic, piezoelectric, etc.), select an optimized solution for integration into the suspension of a typical hybrid/electric vehicle, and evaluate the overall energy efficiency of the proposed system [13]. This is a name given to an exciting modern technology that translates into being able to make shock absorbers not only dampers but also generators that recover energy. These systems are supposed to replace older hydraulic types of shock absorbers that use up kinetic energy from suspension oscillations and dissipate it into the environment in the form of heat, with which energy can be harvested into usable electricity [9].

From a constructive point of view, regenerative shock absorbers can be classified into several categories, depending on the energy conversion principle used: electromagnetic, piezoelectric, hydraulic with electrical generation, and electrostatic. Among them, electromagnetic dampers are the most studied and used in the experimental phases, due to their higher efficiency and mechanical robustness [2], [4], [7].

This research aims to promote the theoretical model that can be technologized, as well as to somehow highlight the advantage of its real use in sustainable mobility. Renewable shock absorbers will become very recognized in those days when any design of a propulsion system strictly respects energy efficiency, as Asif, A. et al. did in their research. This will allow achieving climate neutrality goals and maximize any available energy resources [6], [8, 9].

2. Theoretical Background

Shock absorbers are one of the most important elements of the suspension system, with their function being that of absorbing vibrations and sustaining the stability of the vehicle [7], [10]. In theory, dimensions of shock absorbers (diameter of the cylinder, piston stroke, and diameter of the rod) are said to influence hydrodynamic parameters. The volume of oil, governed by the displacement of the shock absorber, is to maintain good pressure so that there should be no cavitation and easy heat dissipation [3], 12]. A classical approach based on fluid dynamics (Navier-Stokes equations) shows that the damping forces depend on the viscosity of the oil, the speed of the piston, and the geometry of the valve. In addition to these, modern models considered thermal effects on the oil, since increased heat may alter its properties [5], [9]. Thus, the efficient design of shock absorbers should represent a compromise between their dimensions, the volume of oil, and the dynamic behavior [10], [13].

The road on which a vehicle travels plays an important role in assessing the behavior of the shock absorbers, with bumps and potholes producing dynamic stress that reveal the suspension behavior [1], [6]. A well-characterized road allows the analysis of the shock absorber in real conditions, simulating various load scenarios and speeds, which is shown in Figure 1.

1.**Total length:** 200 meters

2.**Travel time:** 20 seconds (average speed of 36 km/h)

3.**Bumps:**

-Maximum height: 13 cm

-Minimum height: 4 cm

4.**Negative unevenness** (potholes):

-Maximum depth: 9 cm

-Minimum depth: 4 cm

5.**Distance between obstacles**: variable (2–6 meters)

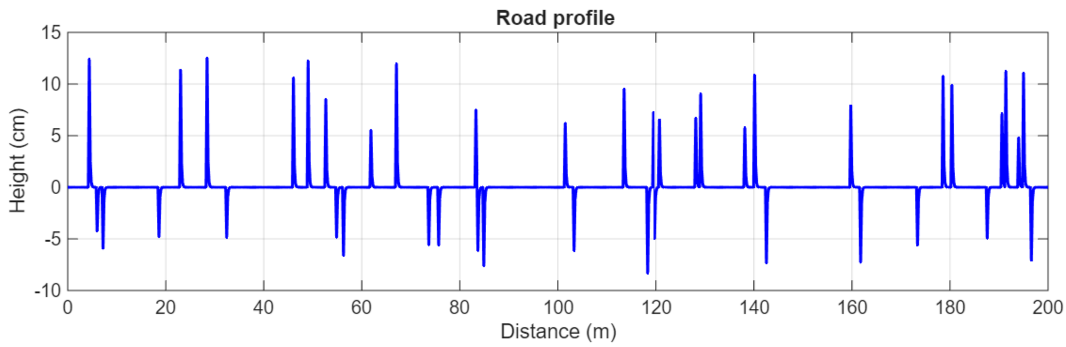

Fig. 1. *Road profile diagram*

The vehicle's shock absorber responds dynamically to these demands, being forced to absorb and dissipate the energy from impacts and vibrations generated by road irregularities. In areas with deep potholes, the shock absorber compresses quickly to absorb the shock, while when driving over bumps, it expands to maintain wheel contact with the road surface and ensure vehicle stability [8], [13].

This task is very vital to the modern suspension systems when considering shock absorber sizing. It involves mathematically treating forces and pressures, speeds, and operating frequencies processes to evaluate the shock absorber dynamic behavior under varying load conditions, from smooth to unpaved roads with severe obstacles [2], [4], [11].

Calculation of the damping force

Each shock absorber supports a fraction of the vehicle's total weight (m_{tot}). For an ideal 50/50 distribution:

$$F_{static} = \frac{m_{tot} \cdot g}{4} \tag{1}$$

where m_{tot}= total vehicle weight (1500 kg).

Dynamic force:

$$F_{total} = F_{static} + C \cdot v_p \tag{2}$$

where v_p= piston speed, C= damping coefficient.

Calculation of internal pressure

The pressure in the cylinder is determined by the force applied to the piston area:

$$P = \frac{F_{total}}{A_p} \tag{3}$$

with $A_p = \pi \left(\frac{D_p}{2}\right)^2 - \pi \left(\frac{D_t}{2}\right)^2$ - effective area, considering the piston rod, Dp= 34 mm (piston diameter), Dt= 12 mm (rod diameter)

Limitations (cavitation)

At high speeds, the pressure drops below the vapor pressure of the oil, causing cavitation:

$$P_{critic} = P_0 - \frac{1}{2}\rho v_p^2 \tag{4}$$

P_0=20 bar (working pressure), ρ=900 kg/m3 (oil density).

$$v_p > 1.5\frac{m}{s}: P_{critic} < 0. \tag{5}$$

Piston speed and working frequency

Piston speed (vp)
For a road with sinusoidal bumps of amplitude A=0.1 m and frequency f=2 Hz:

$$v_p(t) = 2\pi f cos(2\pi f t) \tag{6}$$

Own frequency of the suspension
The natural frequency f_n depends on the mass of the vehicle:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m_{susp}}} \tag{7}$$

k= 25000 N/m (spring rigidity), *Msusp*= $\frac{m_{tot}}{4}$ (suspension mass).
To analyze the behavior of oil in the damper, it will be used the Navier-Stokes equations for incompressible fluids.

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\nabla p + \mu\nabla^2 + f \tag{8}$$

Reynolds Number for laminar stability

$$R_e = \frac{\rho v_p D_h}{\mu} \tag{9}$$

D_h= 5 mm (hydraulic diameter of the orifice), μ=0.1 Pa*s.

Velocity distribution in the orifice, for laminar flow between parallel plates

$$v_z(t) = \frac{\Delta p}{4\mu L}(R^2 - r^2) \tag{10}$$

R=radius of the hole, L=orifice length, Δp=pressure difference

Average speed

$$v_z(t) = \frac{\Delta p \cdot R^2}{8\mu L} \tag{11}$$

Calculating the pressure drop – the Hagen-Poiseuille equation for laminar flow

$$\Delta p = \frac{128\mu L Q}{\pi D_h^4} \tag{12}$$

$Q = v_p \cdot A_p$ (volume flow rate), A_p=piston area.

2.1. Shock absorber system

This sub-chapter focuses on the development of a complete damping system for automotive vehicles, including the design and analysis of a hydraulic shock absorber in complete configuration with its supporting and fixing elements. The proposed system integrates four main components: the hydraulic shock absorber body, the supporting coil spring, the upper mounting bracket and the lower mounting bush. This configuration represents the standard solution adopted in the modern automotive industry.

Liwei, D., et al. mention that designing an efficient damping system requires an integrated approach that considers both the functional aspects of the shock absorber itself and the auxiliary elements that ensure its optimal fixation and operation within the suspension assembly. The entire assembly is designed to function as an integrated system, in which traditional damping components collaborate with energy regeneration elements without compromising suspension performance, the whole assembly and sub-systems for the shock absorber is presented in Figure 2 below.

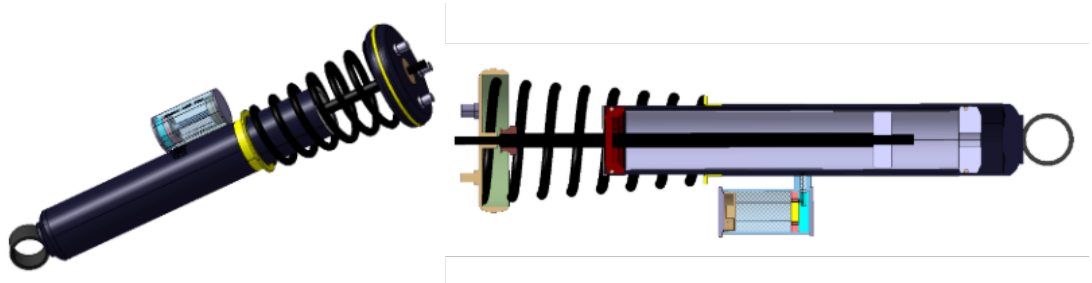

Fig. 2. *Proposed model for shock absorber*

The analyzed regenerative shock absorber consists of six main component systems that collaborate to provide both the traditional damping function and the energy recovery capacity. The Inner tube assembly includes the inner tube, the main piston, the valve system and the hydraulic channels, being responsible for generating the damping forces by controlling the fluid flow. The piston rod assembly includes the main rod, the seals and the guide system, ensuring the precise transmission of the movement and the sealing of the system. The outer tube forms the protective envelope and provides the mechanical strength, while the fixing systems - the upper support (top mount) and the lower mounting point (lower mount) - ensure the rigid connection with the vehicle chassis.

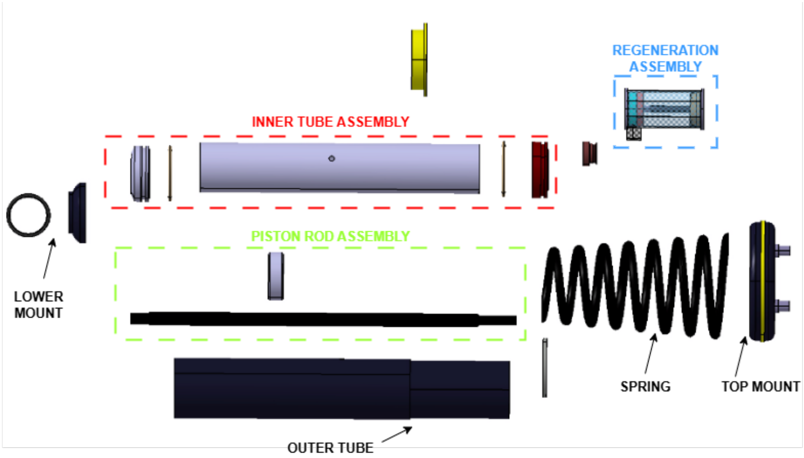

Fig. 3. *Main components for shock absorber*

The technical parameters presented in Table 1 define the functional characteristics of a medium-sized hydraulic shock absorber, typical for automotive applications.

The dynamic performance of the shock absorber is delimited by critical operational parameters: the maximum stroke of 150 mm provides the necessary flexibility to absorb significant road irregularities, while the maximum pressures of 25 bar in compression and 20 bar in relaxation define the safety limits of the hydraulic system.

Characteristics of the shock absorber Table 1

Parameters	**Value**
Cylinder diameter	34 mm
Rod diameter	12 mm
Effective piston area	$9{,}08\text{x}10^{-4}$ m^2 (calculated)
Oil volume	220 ml
Oil viscosity	0.1–0.3 Pa·s (at 20°C)
Maximum stroke	150 mm
Maximum pressure (compression)	25 bar
Maximum pressure (rebound)	20 bar
Damping force	100–1500 N (for v = 0.36 m/s)

2.2. Regeneration module

The fundamental principle of a similar energy recovery system is the capture of hydraulic pressure fluctuations that occur in the shock absorber mechanism.

It has been designed to provide separate hydraulic passages for forward and return, which maximizes the capture of pressure differences that occur during both the compression and rebound phases of the shock absorber. The forward circuit receives high-pressure oil during compression, the return circuit receives low-pressure oil during the rebound phase, and continuous energy conversion occurs throughout the entire shock absorber stroke.

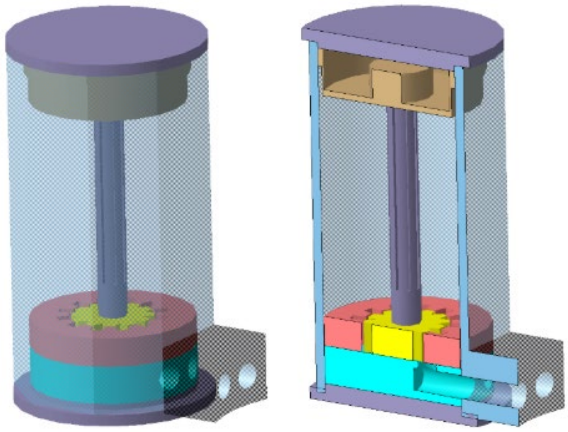

Fig. 4. *Regeneration module model*

The hydraulic energy thus captured is converted into mechanical rotational energy by means of a high-precision hydraulic pump/motor assembly.

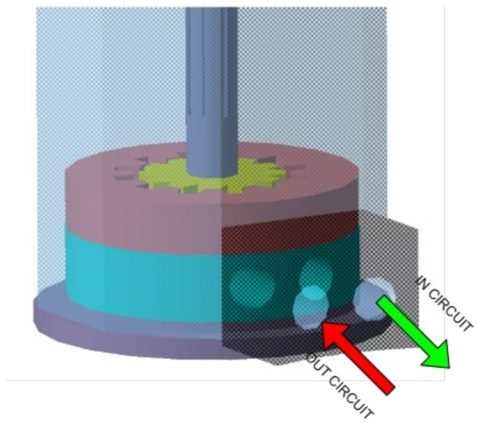

Fig. 5. *Fluid flow for oil*

The electrical energy recovery system is based on the pressure accumulated inside the inner tube of the shock absorber, during its operation. It has an inlet for the liquid found, which is then distributed inside the regenerative unit, shown in Figure 6.

The principle of operation and its component elements are relatively simple, for a construction as simple as possible. Among its functional elements, there are the outer tube of the unit, a body for distributing the liquid round and round, a set of wheels that allow the circulation of the liquid, and the latter drives a rod with the help of which the energy is distributed to the electronic components.

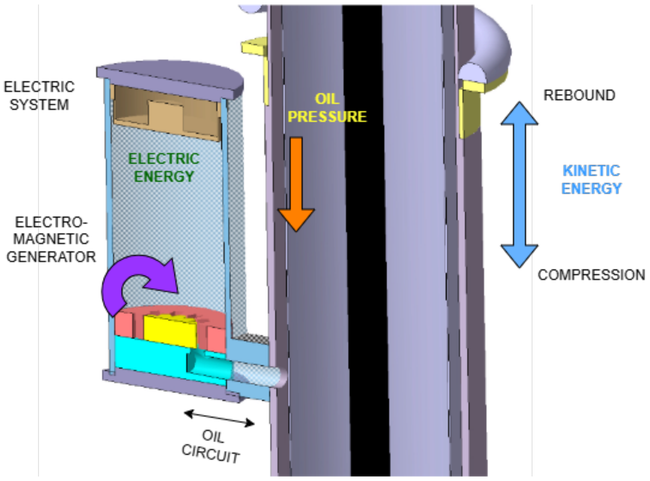

Fig. 6. *Working flow for the regeneration assembly*

This pump converts the fluctuating hydraulic pressure into rotational motion of a shaft.

The rotational motion is then transferred to a permanent magnet generator (PMG), which operates without the need for external excitation, making it suitable for compact applications. This generator converts the mechanical rotation into direct electrical current (DC), which can be stored or fed into the hybrid vehicle's powertrain system.

A schematic of the hydraulic system from Figure 8 below shows the complete fluid supply circuit that captures and converts the mechanical energy generated by the movement of the vehicle's suspension. The system starts with a conventional hydraulic shock absorber, which has been modified for energy recovery applications by fitting this special regeneration module.

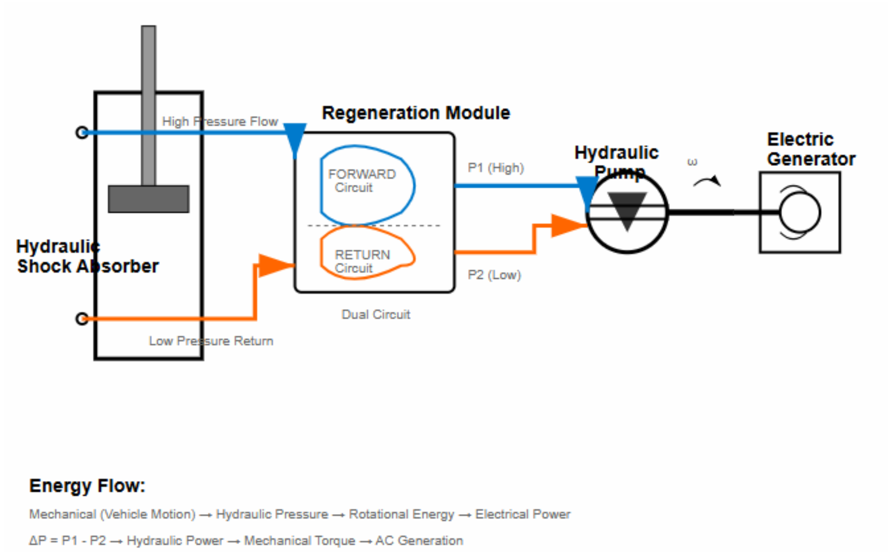

Fig. 7. *Hydraulic system diagram*

Dual-stage relief system with primary valve set at 25 bar and secondary at 10 bar prevents system over-pressurization. Spring-loaded design ensures immediate response to pressure spikes. Adjustable flow restriction valves regulate oil flow rates, preventing turbine over-speed conditions and maintaining optimal energy extraction efficiency.

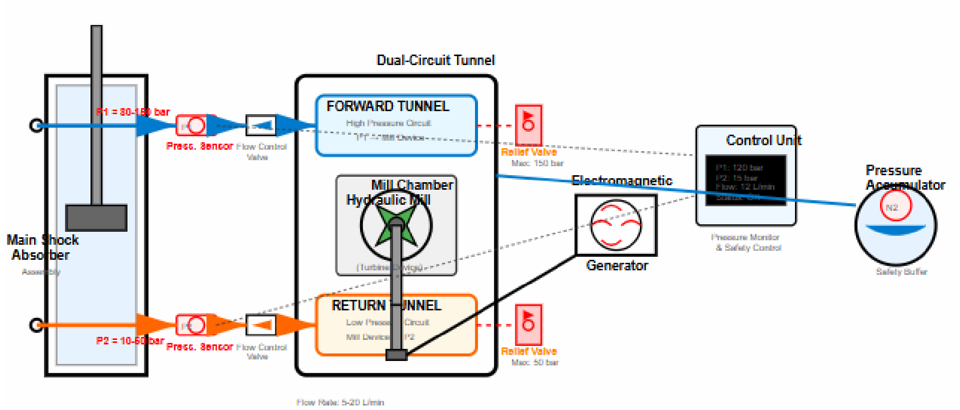

Fig. 8. *Hydraulic oil circuit with safety systems*

This conversion stage is essential to the efficiency of the system, as it transforms the oscillatory variations in hydraulic pressure into a smooth rotational motion, suitable for generating electrical energy. The hydraulic pump is specifically designed to operate efficiently over a wide range of pressure differences and flow rates, adapting to the variable nature of the vehicle's suspension dynamics.

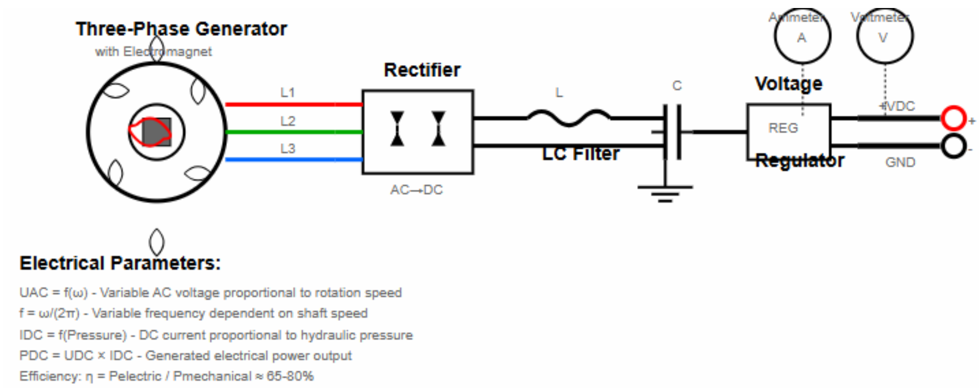

Fig. 9. *Electrical system diagram*

The final stage involves electromagnetic power generation through a three-phase generator, highlited in Figure 10 equipped with a permanent magnet rotor and electromagnetic field control. This generator converts the mechanical rotational energy into three-phase alternating current, which is subsequently processed through a comprehensive power conditioning system [4], [11, 12]. The electrical output is rectified, filtered, and regulated to provide stable DC power suitable for integration with vehicle electrical systems, ensuring compatibility and reliability under all operating conditions [3], [5].

The final DC power output is delivered through dedicated positive and negative terminals, providing clean, regulated electrical power suitable for battery charging, auxiliary system operation, or grid-tie applications in stationary installations. The output characteristics are optimized for automotive applications, with voltage levels compatible with 12V, 24V, or 48V vehicle electrical systems [2, 8, 9].

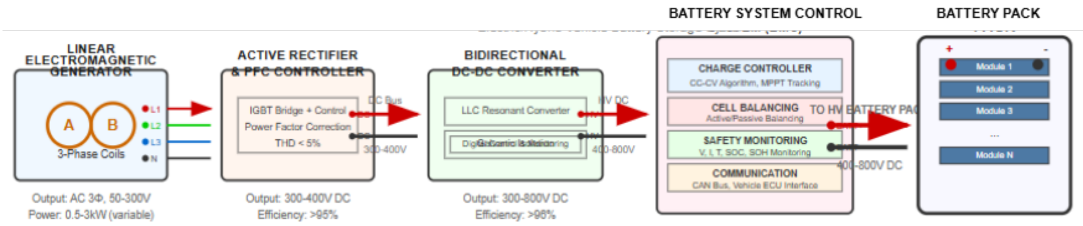

Fig. 10. *Energy storage system.*

The energy storage process is managed by an integrated Battery System Control (BSC) that ensures safe and optimal charging of the vehicle's lithium-ion battery pack. The BMS employs a Constant Current-Constant Voltage (CC-CV) algorithm with Maximum Power Point Tracking (MPPT) to maximize energy capture while protecting the battery. The system presented in Figure 11 can deliver charging currents of 50-200A and includes comprehensive safety features such as overvoltage, undervoltage, overcurrent, and overtemperature protection.

3. Modelling and Analysis

Computational modeling and analysis are fundamental steps in the development and optimization of modern regenerative damping systems. By using advanced simulation tools, the dynamic behavior of the complete system can be evaluated before physical realization, allowing the identification of potential problems and the optimization of operating parameters under controlled conditions. This chapter focuses on the development of a complete mathematical model of the regenerative damping system and its detailed analysis using the MATLAB Simulink and Simscape simulation platforms.

The integrated model allows the simulation of complex interactions between pneumatic, hydraulic, electrical and electronic components, providing a holistic perspective on the system's behavior under various operational conditions.

The Simulink and Simscape simulation tools provide an ideal environment for dynamic system analysis, allowing the creation of complex schemes that include both input elements - road profile, loading conditions, control parameters - and output elements - damping forces, regenerated energy, performance parameters.

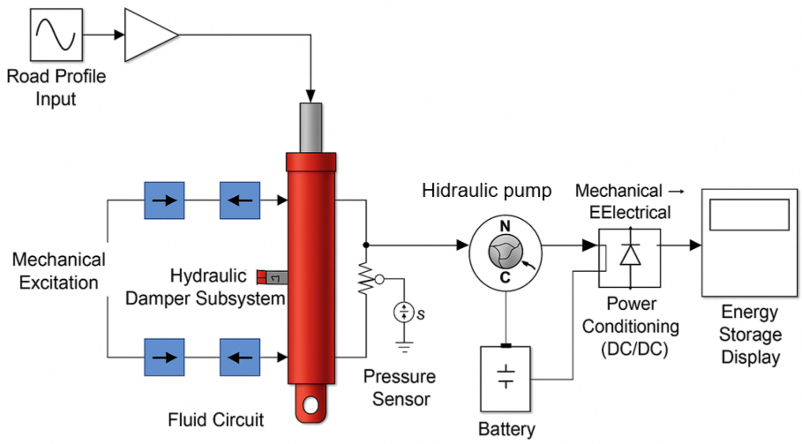

Fig. 11. *Simulink flow diagram.*

The Simulink diagram from Figure 12 above shows the complete model of the regenerative damping system, organized into three main energy conversion stages. The Road Profile Input generates the mechanical excitation that simulates the road conditions and is transmitted through the amplifier to the hydraulic damper system and generates the fluid flows monitored by the pressure sensor. The hydraulic energy is then converted by the hydraulic pump into rotational mechanical energy, which is subsequently transformed into electrical energy by the integrated generator.

Figure 13 illustrates the dynamic response of the suspension to the bumps of a simulated route, highlighting the interaction between the suspension system and obstacles on the road. Analysis of the graph reveals two types of characteristic responses: (1) steep peaks when bumps meet (e.g. at 5 and 10 seconds), where the suspension compresses rapidly to absorb impact energy, and (2) sudden drops when crossing potholes (at 7 and 15 seconds), when the system expands to maintain wheel contact with the ground. The oscillations that follow each disturbance are progressively damped, demonstrating the efficiency of energy dissipation by the shock absorber.

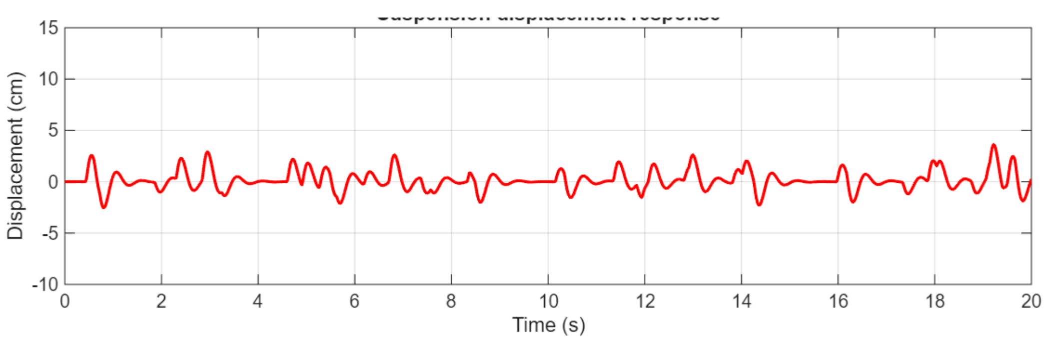

Fig. 12. *Displacement response*

The configuration with hydraulic motor, generator and DC-DC converter, completed by the sensor network for monitoring critical parameters (pressure, flow, torque), ensures an optimized conversion of mechanical energy into usable electrical energy.

The implementation of this scheme in Figure 14 in the Simulink and Simscape environment allows the theoretical validation of the concept and the optimization of operating parameters before physical realization, thus contributing to the development of a viable solution

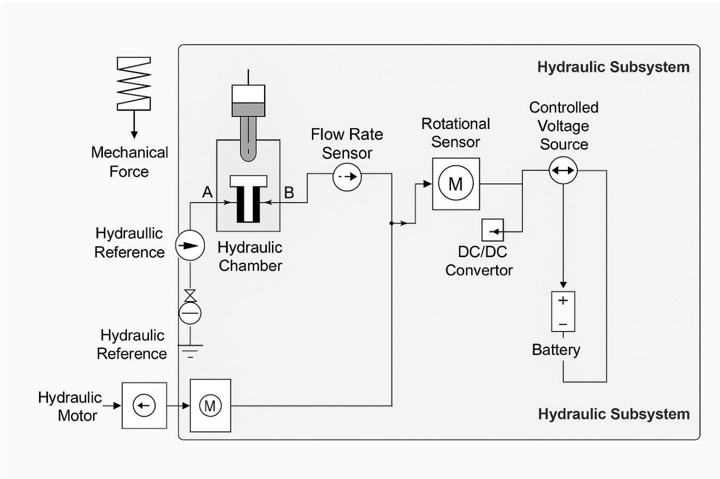

Fig. 13. *Suspension hydraulic-electric flow system*

4. Results and Discussion

This chapter presents the comprehensive analysis of the regenerative shock absorber performance obtained through Simulink simulations. The evaluation focuses on four fundamental parameters that characterize the energy recovery capabilities of the proposed system: damping forces, piston velocity dynamics, cumulative electric energy output, and instantaneous electric power generation.

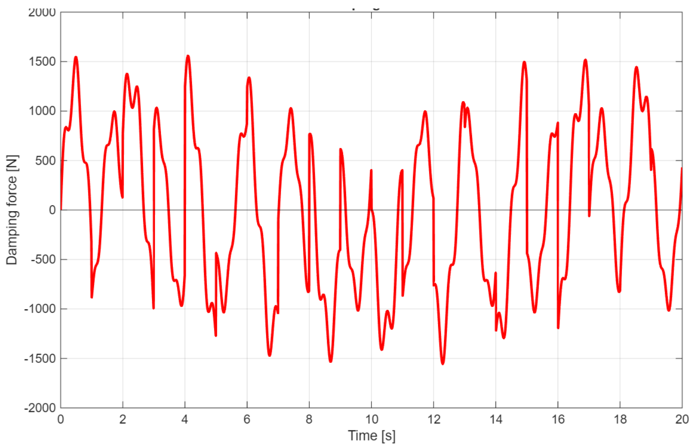

Fig. 14. *Damping forces values*

In this phase, the contribution of the damping force is positive and high, since the speed of the piston is high and the oil opposes the movement.

The graph registers a peak of force (in the upper area, close to 1570 N) at the moment when the piston reaches its greatest compression.

The piston speed is high but in the opposite direction, so the damping force has a different direction, but it is maintained as a controlled resistance, which reduces vibrations.

On the graph presented in Figure 15, the force decreases, but not below a stable minimum value (~630 N), because the shock absorber is also designed to provide resistance in rebound, to avoid uncontrolled jumps of the suspension.

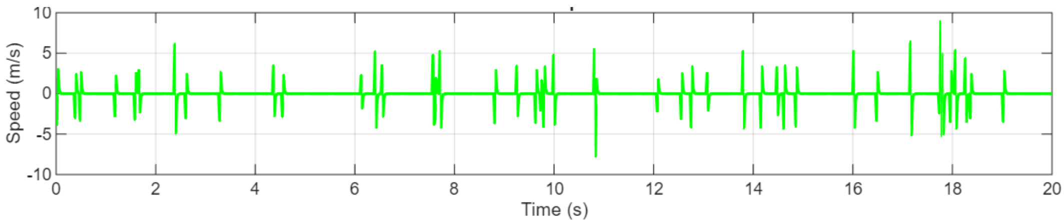

Fig. 15. *Piston speed values*

The velocity values from Figure 16, vary in a range of approximately -8 m/s to +6 m/s, with a higher concentration of data in the range -4 to +4 m/s. This asymmetric distribution suggests that the piston tends to have slightly higher velocities in the compression phase (negative values) compared to the extension phase (positive values), which is typical for damping systems where the hydrodynamic characteristics differ between the two operating phases.

From a frequency perspective, it is observed that most velocity events are concentrated around low and medium values, with rarer peaks reaching extreme values.

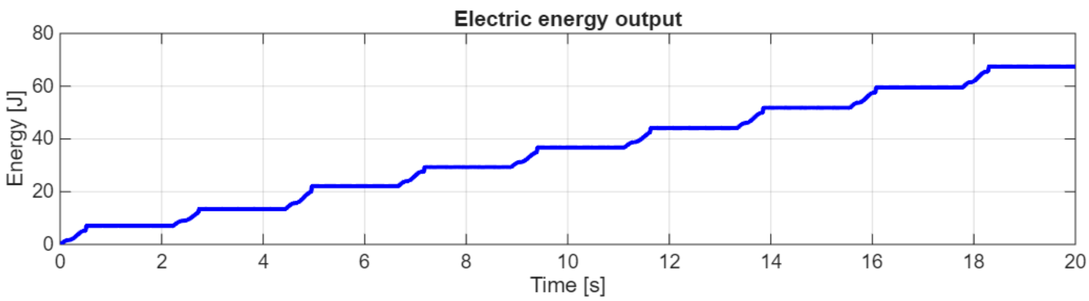

Fig. 16. *Electric energy output*

The energy curve profile highlights the incremental nature of the energy recovery process, with periods of more pronounced growth alternating with areas of slower progression. This variability directly corresponds to the piston speed values analyzed previously - the areas with a steeper slope coincide with the moments when the piston speed reaches higher values.

The graph from Figure 17 shows an increase from approximately 8 J at the start of the simulation to approximately 62 J at the end, representing the total energy accumulated in the storage system.

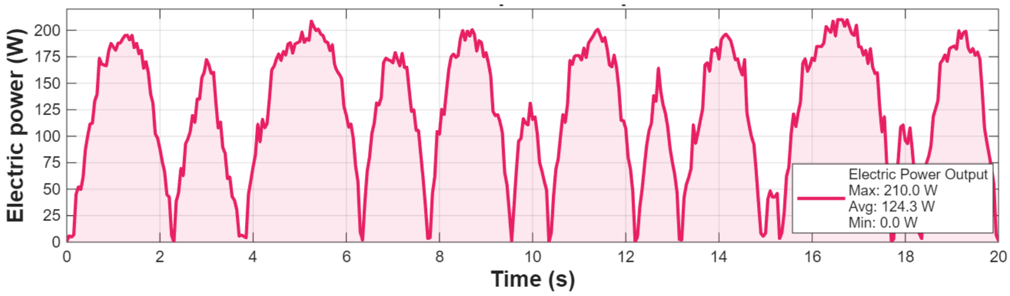

Fig. 17. *Electric power output*

The power oscillates between 0 W and a maximum peak of 210 W, with an average value of 124.3 W, indicating a remarkably high energy efficiency of the regenerative system, as from Figure 18 above.

The power profile shows a typical pulsating shape, with sharp peaks followed by periods of low or zero power. This characteristic directly reflects the dynamic behavior of the piston - the power peaks correspond to the moments when the piston speed reaches maximum values (positive or negative).

5. Conclusions

The study carried out on the regenerative shock absorber has demonstrated that the integration of an energy recovery module into a conventional damping system can significantly improve the overall energy efficiency of modern vehicles. The results obtained through modelling and simulations in Simulink highlight that the proposed system can convert a considerable part of the dissipated vibration energy into electrical energy, with average power outputs exceeding 120 W under typical operating conditions. This confirms that regenerative shock absorbers represent a feasible solution for supporting the charging process of hybrid and electric vehicle batteries.

Another important conclusion concerns the dual role of the system. On the one hand, it maintains the traditional damping capacity of the suspension, ensuring stability and comfort. On the other hand, it introduces an energy recovery function that can reduce the dependence on external charging sources and increase the autonomy of electric vehicles.

Finally, the work underlines the importance of further improving studies and experimental validation. Future research will focus on increasing conversion efficiency, minimizing additional mass and mechanical complexity, and ensuring the long-term reliability of the regeneration module in real operating conditions.

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