SECTION 27. Transport.

Jacota Veronel-George
postgraduate student, University
Polytechnica Bucharest
veromyx@gmail.com

EVALUATION THE RECOVERY ENERGY FROM AUTOMOBILE SUSPENSION BY SIMULATION AND IN ROAD CONDITIONS

Abstract: The purpose of this paper is to verify the possibility to recover the dissipated energy from automobile suspensions, using a electric system who replace the shock absorbers, by simulation and testing in road conditions. The both verifications use a combination between three road category and four speed drives. The analyzed system contains a mechanical part, who transforms the translation body car movement into rotational movement and an electric generator. The results indicate the important quantity of energy recovered during the test on category of road with biggest irregularities, even the drive speed is lower. For the superior category of the road surface, the recovery energy is significant only at high speed.

Key words: Category of roads; suspension; shock absorber; energy recovery system; electric generator.

Language: English

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1. Introduction

The recovery energy from automobile suspension is one of the newest fields of research in automotive industry. All the subcomponents with impact for reduce the fuel consumption as engine, aerodynamic, transmission, tires were achieve the limits because the high price or the new technology demanded. Automotive suspension is a potential source of energy supply continuously due to its condition as long as the car is in motion. The energy dissipated by the suspension dampers can be transformed into electric energy using an electric generator instead of a damper.

The purpose of this paper is to verify the process of recovery the energy from automobile suspension, in terms of simulation and measurement the energy provided by a system, who replace the damper suspension. The system consists of a mechanical system who transforms the body car translation into rotational movement, an electric generator for producing the energy and an electronic control system. The measurements of energy were simulated and tested using a medium class of automobile, in three road conditions and with four different driving speeds.

Fundamental research for the system used to recover the dissipated energy into an automobile suspension is beginning from 1980's, [1-4].

The researches [5-9] describe the functional principle of the system PGSA suspension (Power-Generating Shock Absorber), which take the oscillations from automobile suspension and transform it into electricity using a linear electric generator. The lower part contain the magnets and the the coil. In the compression and rebound strokes voltage is generated, who will be stored into battery.
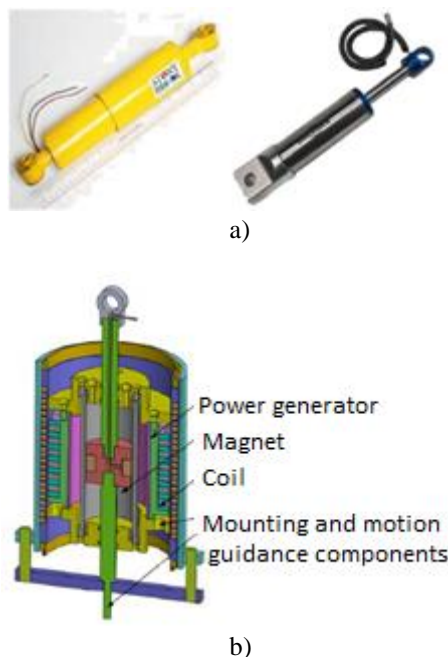
a)

b)

Figure. 1. PGSA Suspension Energy Recovery System, [5]
a) presentation of the system; b) details concerning the system

The attempt was done at speeds of 32km/h and 48km/h. The electrical power provided from all suspensions is maximum 67,5W and an average of 19,2W continuous power, [5].

The papers [10-13] describes the recovery energy system used a pinion and rack-electric gear, which transforms the displacement of the automobile body into electric generator rotation.

During the vehicle is running at 96km/h on high road category [14], the system can produce a total power between 100W and 400W. When the vehicle is running on road irregularities ± 100mm with speed of 100 km/h, the system produce the maximum power 980W, [10].
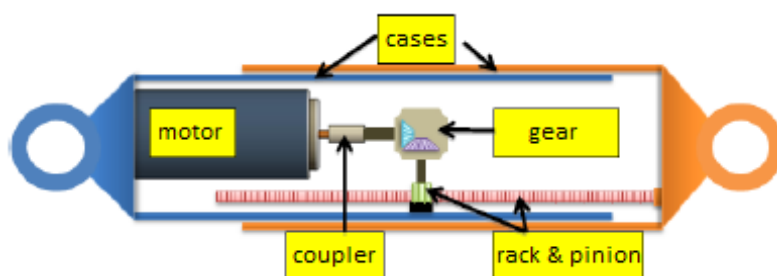
Figure 2. System with pinion and rack-electric gear, [10]

The paper [15] presents the system eROT, proposed by Audi automobile manufacturer.
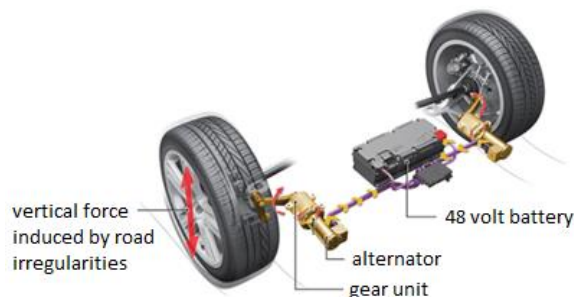
Figure 3. Energy recovery system eROT, [15]

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Audi want to recover the energy by replacing the hydraulic damper with the electromechanical system. The tested system can supply from all suspensions, the power between 3W and 613W for lowest road category, according with [15].

2. Preparation the simulation

In order to simulate the systems suspension operation and to evaluate the recovery energy by the system, there were considered a series of parameters: road profile, automobile characteristics, suspension and electric generator parameters, simulation conditions

The road profile is comprised only the microstructures of running way. This is divided into three classes, according with the high of road irregularities (Δh) measured in mm, [14]:

- ISO A-B, $\Delta h = \pm 15$ mm;
- ISO C-D, $\Delta h = \pm 50$ mm;
- ISO D-E, $\Delta h = \pm 100$ mm.

The automobile characteristics used in simulation are the followings: $m_{S2} = 23$ kg, [16]; $m_2 = 459$ kg, [19]; $m_{a2} = 845$ kg, [19]; $k_{S2} = 28500$ N/m, [17]; $c_{S2} = 1725$ N·s/m, [18]; $k_{t2} = 165000$ N/m, [18]; $c_{t2} = 3430$ N·s/m, [18].

The normal suspension itself includes the spring and the damper. The suspension support the body car mass. The tire was defined as an independent suspension with the same elements, spring and damper. It was considered the tire stiffness and tire damping. For the modified suspension who contain the recovery energy system, it was replaced the damper with an electric generator, presented in figure 4.
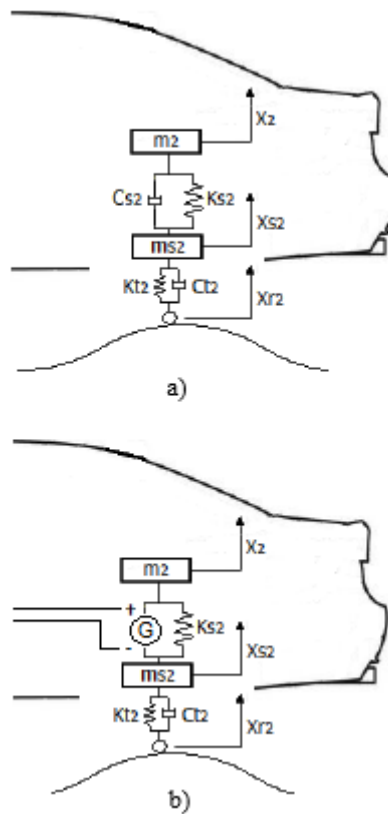

Figure 4. Architecture of suspension subcomponents
a) with hydraulic damper; (b) damper replaced by electric generator

For the suspension equipped with the electric system, the mathematical model includes the entire vehicle, the suspension of front and rear axle, according with the following equations:

$$m_2 \ddot{x}_2 - c_{G2}(\dot{x}_2 - \dot{x}_{S2}) - k_{S2}(x_2 - x_{S2}) = 0 \qquad (1.1)$$
$$- c_{t2}(\dot{x}_{S2} - \dot{x}_{r2}) + k_{t2}(x_{S2} - x_{r2}) = 0$$
$$m_{S2} \ddot{x}_{S2} + c_{G2}(\dot{x}_2 - \dot{x}_{S2}) + k_{S2}(x_2 - x_{S2}) \qquad (1.2)$$

In the relations 1.1 and 1.2 it was replaced the suspension damping c_s with the constant of system equipped with electric generator c_G. The generator damping it was defined according with the relation:

$$C_G = \frac{M_a - M_e - M_i}{n} \cdot k \qquad (1.3)$$

$$M_a - M_e = J \cdot \frac{d\omega}{dt} \qquad (1.4)$$

The electric generator was tested on the bench to determinate the dependence of power in relation with the speed shaft. The curve was calculate like a exponential equation, needed to be integrated on the simulation:

$$P = 3{,}5183 \cdot e^{0{,}0049 \cdot n} \qquad (1.5)$$

The conditions of simulation are the followings:

- simulation performed in only one condition, the car's charging load is 40% from total weight, [20];

- the combination between the constant speeds 20km/h, 40km/h, 60km/h, 80km/h [14] and ISO profiles of roads, [14];

- all profiles road were simulated during 50 seconds.

3. Suspension mathematical model

The suspension model was achieved in the soft Matlab Simulink. The model is applied only to quarter vehicle, respectively half of rear axle. The simulink model consists of two nodes, on which the forces are acting. The first block is represented by the suspended mass and the second one is non-suspended mass. On the suspended mass acts the weight of the respective axle and the elastic force of the suspension and the damping force of the electric generator, act as a result of the driving moments due to the oscillation movement of the suspension, the electric torque and the moment of inertia.

The ratio between the resultant force and the suspended mass represents the acceleration of the suspended mass. By integrating acceleration, the velocity of the suspended mass is obtained and by integrating the velocity it is obtained the displacement of the suspended mass. The non-suspended mass is the second node that receives five forces: the weight of the non-suspended mass, the reaction from the elastic element and damping force of the electric generator, the tire elastic force and tire damping force.
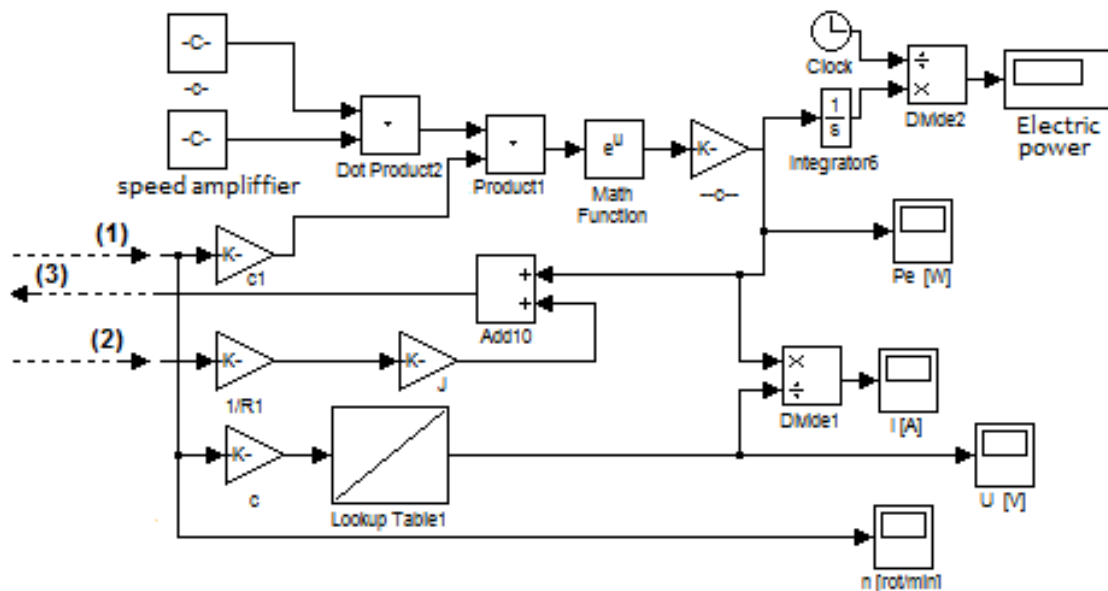

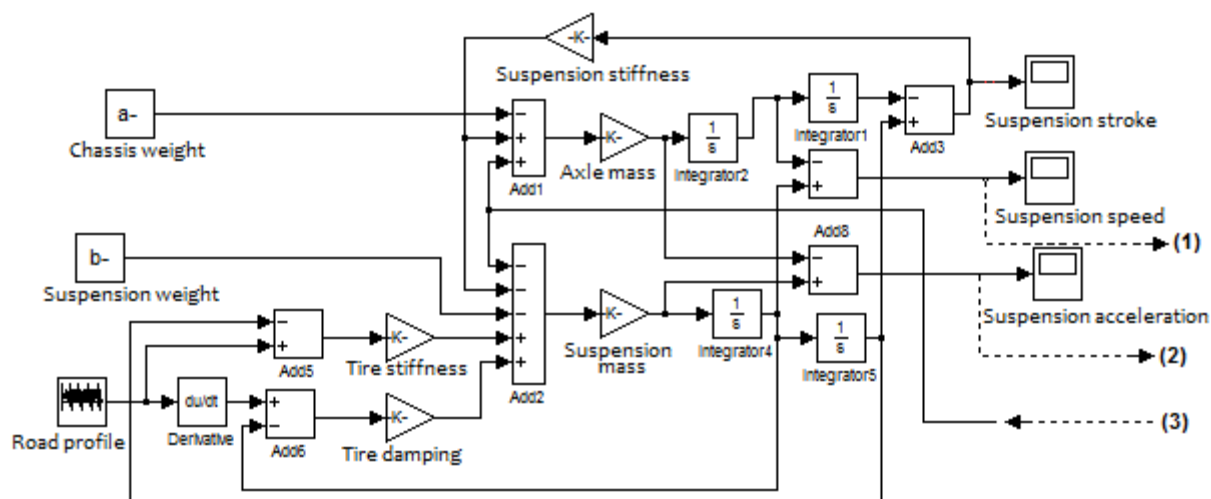**Figure 5. Block structure for mechanical side of suspension**

Figure 6. Block structure for electric side of suspension

4. The recovery energy system

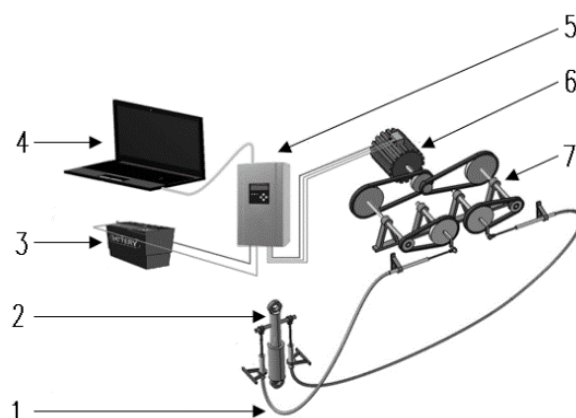The proposed system for recovering recovered energy from vehicle suspension is shown in figure 7 and 8.

Figure 7. The recovery energy system
1-push-pull cables; 2 – slider; 3- battery; 4- laptop; 5- electronic control device;
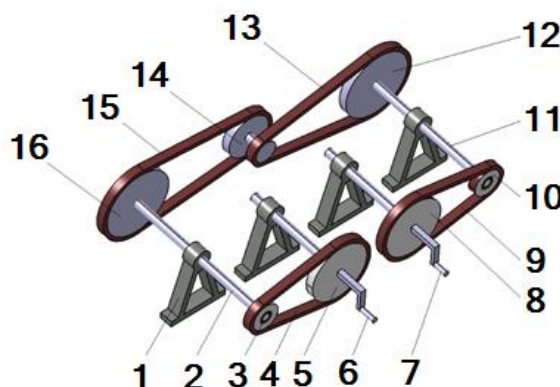**6- electric generator; 7- speed amplifier system**

Figure 8. Speed amplifier system

The slider take the translational movement from automobile chassis and transmit it through push pull cables to the amplification system (figure 8). The cables are cylindrically articulated on the cranks 6 and 7. By means of the chains 4 and 9, the rotation movement is transmitted from the driving wheels 5 and 8 to the unidirectional gears 3 and 10. The already amplified rotation movement is transmitted to the wheels 12 and 16, which transmit the movement to the shaft 14, which is coaxially connected to the shaft of the electric generator. When the suspension is in compression, the translational movement is transmitted simultaneously to the cranks 6 and 7. Only the crank side 6 is active, since the unidirectional coupling 10 does not allow the transmission of the movement. Thus, the speed is amplified to the output to the two-stage electric generator. The same happens in case of suspension when the active branch becomes the one of the coupling 10. In this way, both in compression stroke and rebound, the generator is unidirectional driven.

The equipment used in test contains the followings specifications:
- the speed amplifier system: η_m = 0,68, i_c = 2,13, i_r = 3,03
- the electric generator: η_e = 0,83, n_n = 250 rpm, P_n =300W, P_{max} = 450W (350 rpm), U_n = 12V, [21]
- the tested automobile: Opel Astra Caravan 1.7D, fabrication year 1996, tiers: 175/70 R13, Pt = 2bar
- the road categories: National Road (DN), associated with ISO A-B road from simulation, County Road (DJ), associated with ISO C-D and Country Road (DC), associated with ISO D-E road from simulation

- testing conditions: the automobile charging load is 40% from total weight, [20]; speeds testing 20km/h, 40km/h, 60km/h, 80km/h, [14].
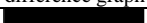
5. Interpretation of results

For the same conditions of simulation and testing, it was obtained a big difference in terms of average recovered power. The simulation results indicate a higher recovered power because is not taking into account the efficiency of system.

In terms of graphic representations form, the difference between the two power graphics appears because:
- the road irregularities from simulation are not the same like road profile from the test
- the sampling frequency for simulation signal is 0,001 second[-1] and for testing signal, the frequency of acquisition is 1 second[-1]
- the simulation taking into account all the roads irregularities and the tested system can take only the irregularities higher than 3mm with the speed bigger than 40km/h to supply the power
- the automobile parameters used for testing, in terms of mass and suspension, can have the different values from specifications

To compare the both categories of supplied power, from simulation and from testing, it was recalculate the simulated power taking into account the global efficiency measured from tested system. The results are indicated in the table 1, also with the relative difference ε between the both measurement types.

Table 1. Average of electric power tested

No.	Road and speed category from simulation	Road and speed category from	Simulation power [W]	Tested power [W]	Relative difference ε [%]	Relative difference graph
1.	ISO A-B; V = 20 Km/h	DN; V = 20 Km/h	1.1	0.0	100	
2.	ISO A-B; V = 40 Km/h	DN; V = 40 Km/h	2.2	0.0	100	
3.	ISO A-B; V = 60 Km/h	DN; V = 60 Km/h	2.8	4.0	42	
4.	ISO A-B; V = 80 Km/h	DN; V = 80 Km/h	8.9	10	12	
5.	ISO C-D; V = 20 Km/h	DJ; V = 20 Km/h	8.4	7.0	16	
6.	ISO C-D; V = 40 Km/h	DJ; V = 40 Km/h	12	10	16	
7.	ISO C-D; V = 60 Km/h	DJ; V = 60 Km/h	14	12	14	
8.	ISO C-D; V = 80 Km/h	DJ; V = 80 Km/h	19	15	20	
9.	ISO D-E; V = 20 Km/h	DC; V = 20 Km/h	14	13	7	
10.	ISO D-E; V = 40 Km/h	DC; V = 40 Km/h	28	25	11	

For the national road at reduced speeds, where the generator cannot supply the energy, the relative difference is 100%. The considerable difference is also for national road at 60km/h. For all the others categories, the relative difference between the simulation and tested powers are under 20%.

6. Conclusions

The difference between the simulation and testing results in terms of recovered energy from suspension, indicate a confidence to use the program simulation. Except the situations where the real system cannot generate the power, the relative difference between the two methods is inferior at 20%, even the conditions are not identically. To reduce the difference between the simulation and test, must be developed a system adapted for each type of suspension and must make the simulation and the test in the same conditions.

To simulate the suspension in better condition, must taking into account the entire vehicle. The actual model is applied only to quarter vehicle, in this situation is eliminated the influence from the others suspensions.

From point of view supplied power of the tested system, the average power is similar comparing to the prototypes analyzed. To increase the quantity of recovered energy is required to improve the system efficiency, to transform the energy of the oscillations of chassis into electric energy even at the small road irregularities. The others requirements to recover the bigger amount of energy are represented by the adapted ratio of mechanical system for each type of road irregularities and to use the controller with higher efficiency to maximize the power.

Regarding the possibility of placing conveniently the system on the car, the systems analyzed so far required their placement in the immediate neberness of the suspension, under the bodywork. In this working environment, the mechanical and electrical equipment must be made taking into account several factors, such as: ensuring the necessary sealing, especially of the electrical equipment, the increased mechanical strength in case of contact with the various obstacles over which the car passes, difficult access to change subcomponents due to positioning under the car. The actual research, consider the robust push-pull cables, to avoid the problems presented above.

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Nomenclature

m_{S2} unsprung mass, corresponding to the rear axle, [kg]

m_2 sprung mass, corresponding to the rear axle (for unladed car weight), [kg]

m_{a2} sprung mass, corresponding to the rear axle (for total car mass), [kg]

k_{S2} rear suspension spring rate (for one spring), [N/m]

c_{S2} rear suspension damping (for one damper), [N·s/m]

k_{t2} tire stiffness rear axle (for one tire), [N/m]

c_{t2} tire damping rear axle (for one tire), [N·s/m]

x_{r2} rear suspension excitation , [mm]

x_{S2} rear suspension displacement, [mm]

Δh high of road irregularities, [mm]

M_a active torque generated in suspension motion, [N·m]

M_e electric resistant torque, [N·m]

M_i inertial resistant torque, [N·m]

J inertial torque, [N·m/(rad/s^2)]

ω angular generator speed, [rad/s]

n generator speed, [rot/min]

k transform coefficient torque-force, [-]

η_m mechanical system efficiency, [-]

η_e electric system efficiency, [-]

i_c compression ratio, [-]

i_r rebound ratio, [-]

n_n nominal speed, [rpm]

P_n nominal power, [W]

P_{max} maximum power, [W]

U_n nominal tension, [V]

P_t tire pression, [bar]

ε relative difference, [%]

DN   National Road

DJ   County Road

DC   Country Road

$Z_{1\text{-}}Z_8$ gears teeth number, [-]

R   joint radius, [mm]