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Simulink model of a Regenerative Shock Absorber

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Abstract. The field of the Electric Vehicles (EVs) is becoming a strategic laboratory for new solutions focused on the energy saving and/or the renewable energy sources. Regenerative brakes are well known and already applied in recent cars. In this paper, instead, the attention is focused on a regenerative Shock Absorber (SA), which converts its vibration - induced by the road roughness - in electrical energy. The vibration is transmitted to an electric generator through a mechanical component. Finally, the produced energy can be stored in a super capacitor for a future use. The paper proposes a Simulink-based model of this regenerative SA and compares the energy performance when the vehicle travels roads with different roughness, scientifically defined by means an index, said IRI.

Keywords
Regenerative Shock absorber, IRI, Simulink, Model, Supercapacitor.

1. Introduction

The large amount of green-house gas emissions is caused from the extensive use of the fossil fuel worldwide. So, it needs to replace the fossil fuel energy with renewable clean energy to prevent the worsening of the environmental issues. Moreover, the reduction of the use of fossil fuel can lower the energy costs, even considering that, in USA, the automobiles are responsible of 70% of the carbon monoxide, 45% of the nitrogen oxide and 34% of the hydrocarbon pollution [1]. Vehicles consume over 40% of petroleum in USA and the exhaust causes more air pollution than anything else [2]. The relationship between the vehicle energy flow and the vehicle performance has been studied by researchers in [3], and it results that only about 14%-30% of the energy from the fuel is used to move it. Some results are comforting, considering that nowadays the braking energy recovery system is widespread in the automotive industry [4]. Moreover, as a consequence of the evolution toward smart grids, the vehicles are assuming a strategy value of the electrical grid, leading to opportunities to use the flexibility of the electric vehicles to optimize the peak demands for the electric distribution grids [5]. In a scenario with a high wind and photovoltaic penetration in the system, the electricity prices are determined by the instantaneous energy production. Wind turbines and PV systems are intermittent energy sources [6]-[7], whose production depends on the weather conditions; and this is a criticality for the stability and safety [8]. The criticalities regard the unpredictability of the produced energy and the efficiency of the plants that must be constantly monitored [9-13]. In this scenario, the energy exchange with the electric vehicles is stimulating the researchers in finding new solution, as the Vehicle-to-Grid (V2G) approach. Therefore, the role of the vehicle in supporting the reduction of carbon emissions and in making power systems more efficient is becoming increasingly important. The SA is the component of the vehicle suspension, combined with the suspension spring to filter vehicle vibration due to rough road. Energy from vibrational sources is usually dissipated as hydraulic friction and heat. Traditionally, several researchers have focused attention on the energy wasted in the SAs, examining the feasibility of harvesting energy from the SA, as results in the literature [14-18]. In these papers, the approach was focused on the harvesting of the kinetic energy dissipated by the suspension. Successively, the studies on the regenerative SA have been concentrated on three different categories [19]: electromagnetic, hydraulic and mechanical designs. The first one is based on an electromagnetic method to generate the electric power, based on a linear electromagnetic regenerative SA that uses the electromagnetic induction to convert the kinetic energy of vertical oscillations into electricity [20]. The second category harvests the vibration energy and converts it into electricity, thanks to the oscillatory motion to drive a hydraulic motor, which is connected to a power generator [21]. The third one category is the mechanical regenerative SA, characterized by a greater efficiency than the previous technologies [22]. For this reason, this paper proposes the model of a Mechanical Regenerative SA (MRSA), implementing it in the Simulink environment. The paper is organized as follows. Section 2 introduces the electro-mechanical model, while Section 3 discusses the Simulink model and the simulation results. Conclusions end the paper.

2. Model of the regenerative SA and preliminary results

The MRSA under examination is described in [19] and is schematically represented in Figure 1, where x and F represent the position of the SA and the force due to the vibration, respectively.

The main components of the MRSA are the two coaxial (inner and outer) cylinders, the transmission mechanism, the planetary gearbox, which actives an electric generator that, in turn, charges a supercapacitor.

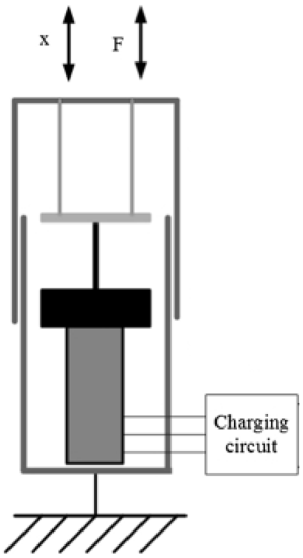

Figure 1. Simplified scheme of the MRSA.

An interesting consideration regards the electricity generation is that the MRSA produces energy for each relative movement between the inner cylinder and the outer cylinder, regardless of whether the movement is a compression or an extension. This happens because the structure of the transmission mechanism solicits the planetary gearbox always in the same direction.
The model will be based on the spring-damper system, considering the rigidity and the dumping of both the shock absorber and the tire, other than their mass. Figure 2 reports the principle scheme of the proposed regenerative SA (on the right) integrated in the standard quarter-car absorber (on the left) [1]. A quarter vehicle suspension system consists of the wheel assembly mass m_1, the quarter vehicle mass m_2, the tyre stiffness k_1 and tyre damping c_1, finally the suspension stiffness k_2 and the suspension damping c_2. The single speed regenerative SA is placed in between the quarter vehicle mass and wheel assembly mass and it provides the additional electromagnetic damping and generates the electrical energy. The variables x_1 and x_2 represent the displacement of the wheel assembly mass and the quarter vehicle mass, respectively; instead, y is the road excitation displacement. The variable B is the magnetic field intensity, the product Bl is the electromechanical coupling constant, being l the total length of the coils; U is the output voltage.
The electrical circuit is reported on the right of the Figure 2, being R_i the coil resistance and L the coil inductance. The electrical power is extracted over the external resistor R_e.

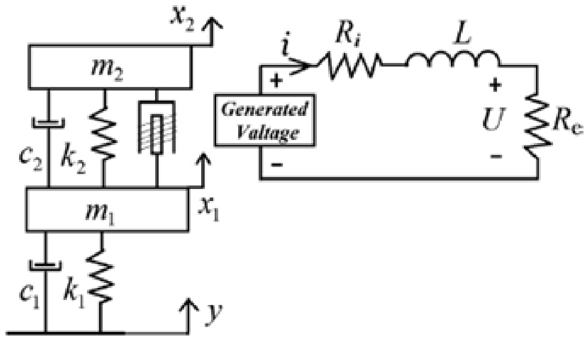

Figure 2. Quarter-car absorber and regenrative absorber.

The electro-mechanical system of Figure 2 is mathematically described by the following equations:

$$\begin{cases} (m_1+m_m)\cdot\ddot{x_1}+(c_1+c_2)\cdot\dot{x_1}-c_2\cdot\dot{x_2}+(k_1+k_2)\cdot x_1-k_2\cdot x_2-c_1\cdot\dot{y}-k_1\cdot y-\frac{BlU}{R_e}=0 \\ (m_2+m_c)\cdot\ddot{x_2}+c_2\cdot(\dot{x_2}-\dot{x_1})+k_2\cdot(x_2-x_1)+\frac{BlU}{R_e}=0 \\ Bl\cdot(\dot{x_1}-\dot{x_2})-L\cdot\frac{\dot{U}}{R_e}-\frac{U}{R_e}\cdot(R_i+R_e)=0 \end{cases} \quad (1)$$

3. Simulink model and simulation results for three cases

The values used for the system under test are reported in the Table 1 [1]. After the modelling, three different case studies will be considered, in order to compare the different amount of energy: *highway, old pavement, rough road*. These different roads are classified on the basis of the International Roughness Index (IRI), which defines the roughness level per km and the speed range. IRI is measured in m/km, i.e. the amount of asperities per km [23,24]. The IRI value, for each case under test, is reported in Table 2, whereas Figure 3 is the Simulink scheme of the regenerative SA of Figure 2. On the left-hand side, a two-ways selector allows to load the characteristic parameter of the road tipology (highway, old pavment, rough road), the length of the path, the speed, and so on. The central part allows to extract the electrical variables of the regenerative SA (voltage and current).

Table 1. Parameters of the system in Figure 2.

	Parameter	**Value**
Wheel assemly mass	m_1	40 kg
Quarter veichle mass	m_2	260 kg
Tyre stiffness	k_1	130.000 N/m
Supsension stiffness	k_2	26.000 N/m
Tyre damping	c_1	264.7 Ns/m
Absorber damping	c_2	520 Ns/m
Electromagnetic coupling	Bl	6.5Tm
Coil resistance	R_i	113Ω
Load resistance	R_e	113Ω
Coil inductance	L	94μΩ

Table 2. IRI (International Roughness Index) for different roads

	Parameter	Value
Highway	IRI	2 m/km
Old pavement	IRI	5 m/km
Rough road	IRI	11 m/km

Finally, the right-hand side allows to store the variables and to plot the time-series of voltage, current, power and energy. For each case under test, fixed the maximum value of the IRI, the roughness is randomly generated. Therefore, in order to evaluate the global effect during a long path, ten repetitions are considered and they cover a path of 10km. Figure 4 reports the time-serie of voltage, current, power and energy for the highway-case, i.e. for $IRI = 2m/km$. The energy diagram is highlighted in blue color for a successive comparison with the other two cases.

Some statistics (min/max/rms value of voltage and currente, etc.) are reported in the first row of the Table 3. Figure 5, instead, reports the time-series of the electrical variables of the second case under test, the old pavement, having $IRI = 5m/km$. The produced energy (blue box) has a linear behavior, as in the previous case, but the final value is higher than the previous case. The statistics are reported in the second row of Table 3.

Finallly, Figure 6 diagrams the time-series of the electrical values of the third case, the rough road, having $IRI = 11m/km$. The produced energy (blue box) is the highest one among the three investigated cases. The statiscs in the third row of Table 3 confirm that the rough road allows the maximum energy recovery.

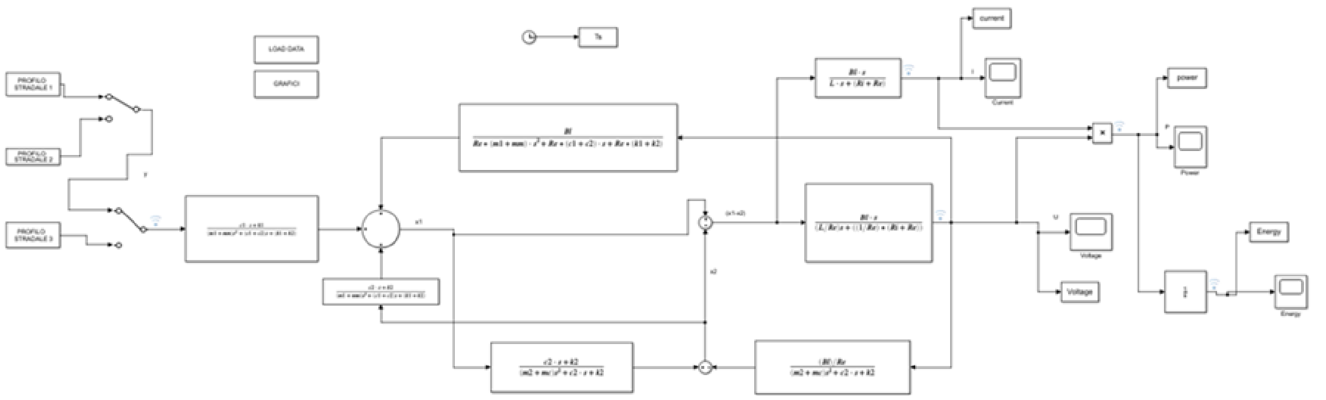

Figure 3. Simulink scheme of the regenerative SA to study three cases: highway, old pavement, rough road.

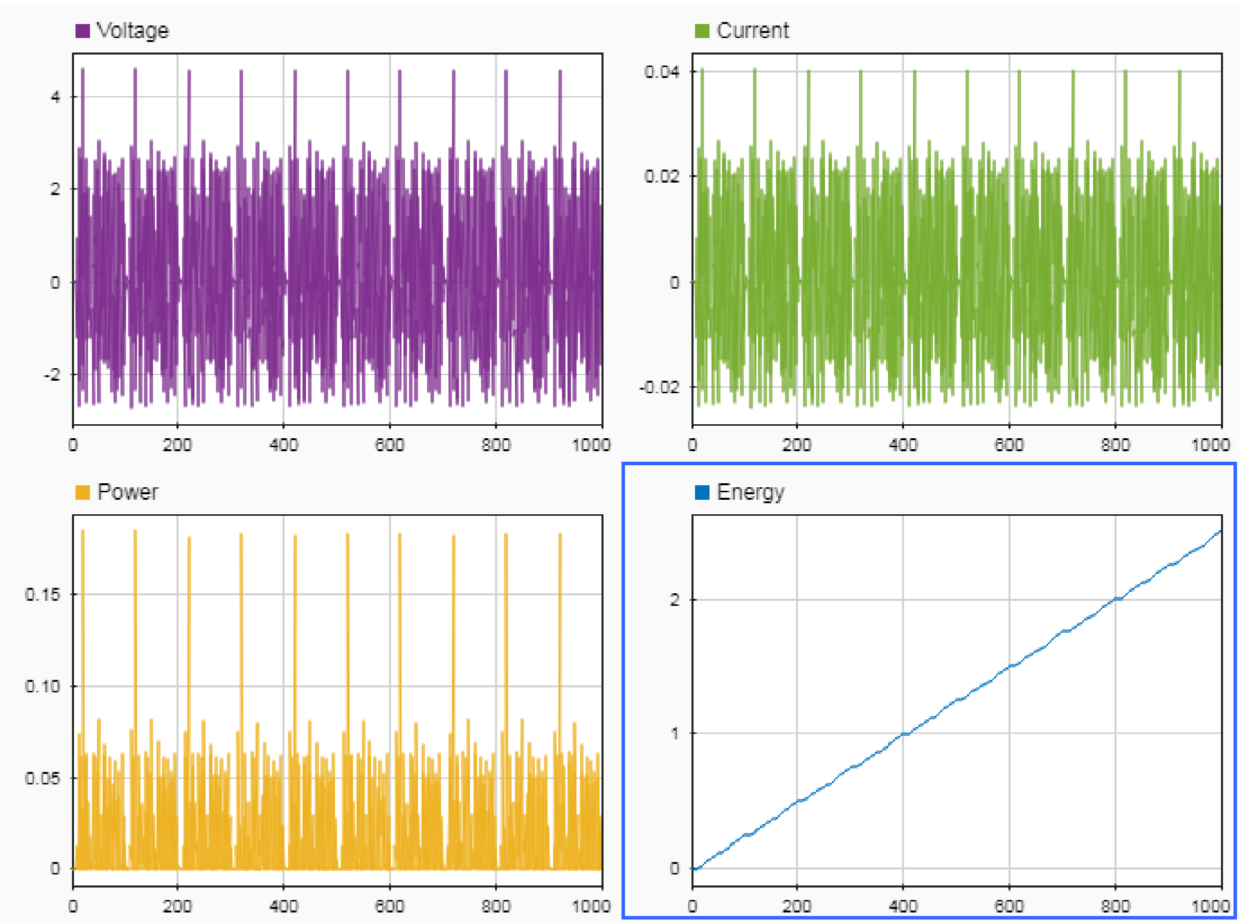

Figure 4. Voltage [V], Current [A], Power [W] and Energy [Ws] for the *highway* case. ($IRI = 2m/km$).

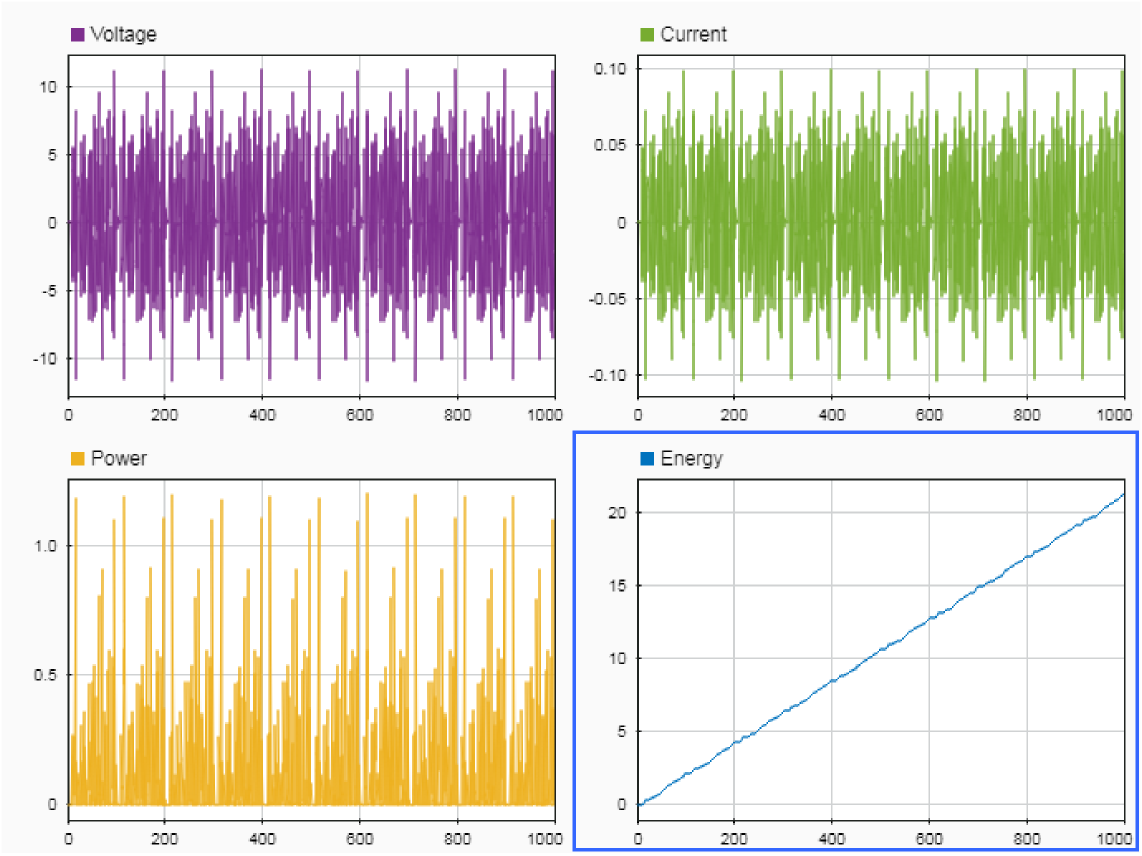

Figure 5. Voltage [V], Current [A], Power [W] and Energy [Ws] for the *old pavement* case ($IRI = 5m/km$).

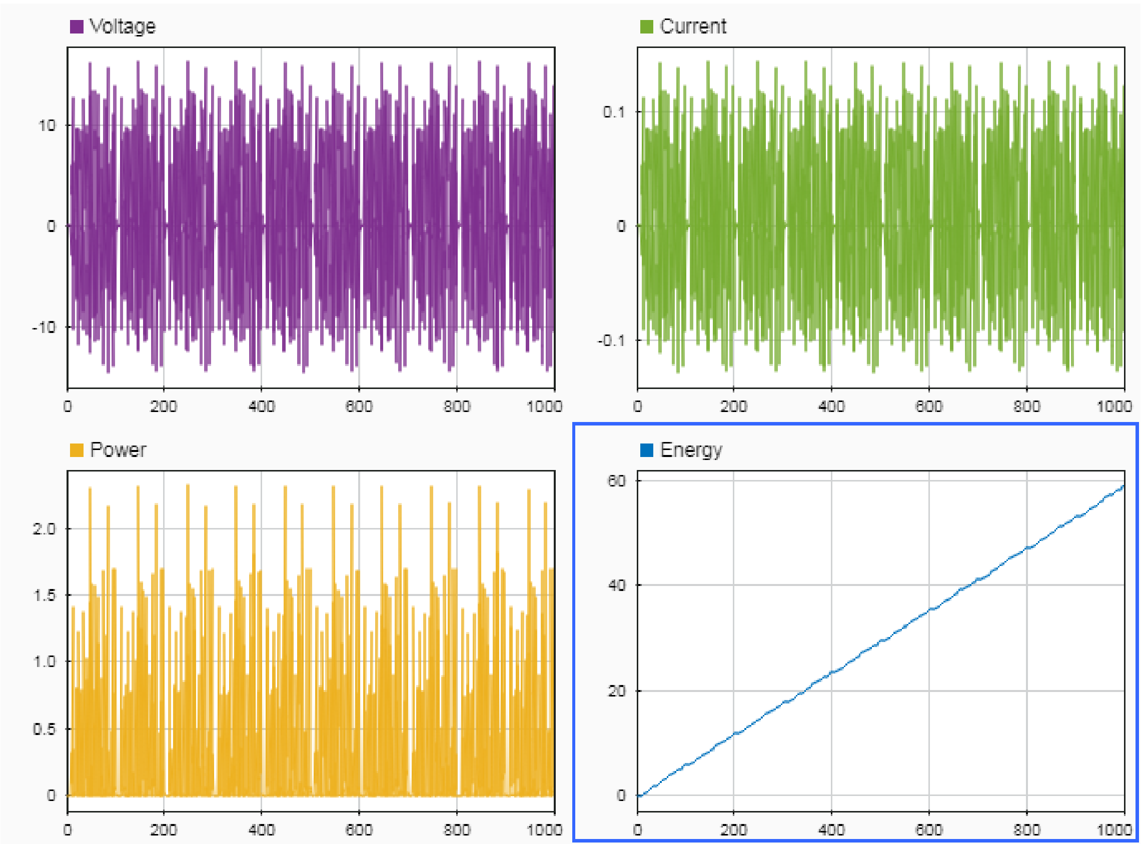

Figure 6. Voltage [V], Current [A], Power [W] and Energy [Ws] for the *rough road* case ($IRI = 11m/km$).

Table 3. Electrical parameters for the three cases under investigation.

	Voltage[V]			Current [A]			Power [W]	Energy[Ws]
	Max	Min	RMS	Max	Min	RMS	Mean value	Max
Highway	4.573	-2,705	0.639	0.041	-0.024	0.006	0.004	2.507
Old pavement	11.193	-11.646	1.921	0.099	-0.103	0.017	0.032	21.247
Rough road	16.189	-14.456	3.208	0.143	-0.128	0.028	0.091	59.100

4. Conclusions

The paper discusses an electro-mechanical system that converts the vibrations, caused by the roughness of the road, into electrical energy, which, on its turn, supplies the electrical devices of the vehicle. The proposed system, implemented in Simulink environment, is based on the classification of the roads by means of the IRI, an index that measures the amount of roughness per km. Three cases with very different values of IRI were studied: highway, old pavement and rough road. As expected, the latter one is the most efficient case, since the maximum energy is produced. It is important to note that other mechanical solutions are studied to gain the amount of the produced energy. Their aim is to double the inductive effect for a single vibration. From the electrical point of view, these systems are similar to the proposed one, but they have a gained electrical source. Thus, the proposed Simulink model can be re-used.

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