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Self-powered Active Suspension

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Abstract

In recent years there has been growing interest in alternative energy source that could satisfy the large demand for energy and guarantees a low environmental impact at the same time. In the automotive field, in particular, many devices to harvest energy has been developed such as regenerative braking systems or regenerative suspension. In this thesis a self-powered active suspension system is proposed in which a single actuator realizes active control of the chassis and regeneration of vibrational energy excited by the uneven road. The actuator is essentially a linear tubular permanent magnet motor that exploit Eddy currents, generated in the stator coils, by the relative motion between the magnets and the coil itself. The actuator is connected to a condenser through controllable relay switches which decide the direction of the current and a variable resistor which decide the amount of the electric current. The latter is proportional to the force provided by the actuator. Thus by controlling the variable resistance it is possible to track the desired force given by a sky-hook control law.

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Introduction

1.1 State Of Art

Suspension is the system of springs, dampers and in case actuators by which a vehicle is supported on its wheel. The fundamental goal of a suspension system is to provide proper steering control and ride quality by minimizing the vibrations due to irregularity of road profile and at the same time maximize the tyre-to-road contact. Too “soft” suspension improve comfort as they deform very quickly adsorbing the roughness of the road, but it can reduce road holding due to the large vertical oscillations of the contact force between tyres and road. On the other hand, a too “stiff” suspension ensures better grip but causes an increase in vertical stresses on the vehicle body which translates in discomfort for the passengers. Moreover when the car accelerates or decelerates, or make a turn, the body of the vehicle is subjected to movements of pitch and roll which also need to be compensated by the suspension. Basically a suspension can be seen as a mechanical low-pass filters which attenuates the effects of a disturbance on an output variable. The output variable is the chassis acceleration or jerk when comfort is the main objective; the tire deflection when the design goal is road handling [1]. Suspension systems can be grouped into three categories: passive, semi-active,active.

1.1.1 Passive Suspensions

Most of the commercial vehicles are equipped with passive suspension systems due to their low cost and simple construction since they are constitute by purely mechanical elements such as springs and dampers; both components work in parallel and are fixed between the wheel supporting structure (unsprung mass) and the vehicle body (sprung mass). The drawback of the passive suspension is that it is not possible to simultaneously maximize both ride comfort and vehicle handling. Moreover their spring and damping coefficient cannot be adaptively tuned according to driving efforts an driving conditions. Therefore a passive suspension can achieve a good trade-off of the two mentioned performance parameters only under the design conditions.

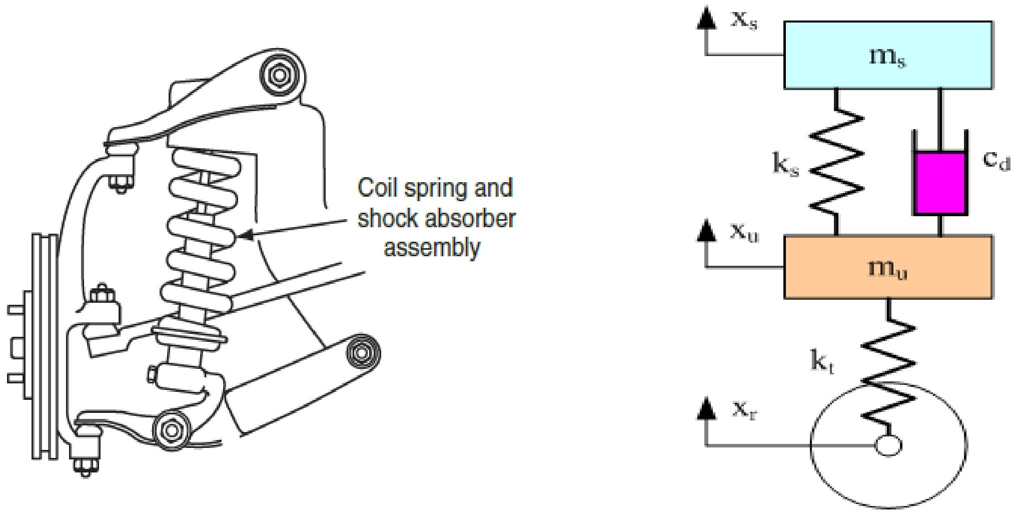

Fig.1 Passive suspension system [2]

1.1.2 Semi-Active Suspensions

In a semi-active suspension system the damping forces can be adjusted by control of the damping coefficient without introducing mechanical energy into the system. Nowadays there are three main technologies which allows to control the damping coefficient in real time: electro-hydraulic dampers magnetorheologiacal dampers (MRD) and electrorehological dampers (ERD). The first one it consists of a solenoid valve which alters the flow of the fluid inside the shock absorber by modifying the size orifice according to the control algorithm; the other two technologies are based on fluid that vary their viscosity if subjected to an electric or magnetic field. A magnetorheological fluid for example is an oil that contains numerous small ferromagnetic particles in suspension. A solenoid embedded inside the damper ,when energized, produces a magnetic field which tends to align the particles in a sort of chain. Therefore the MR fluid behaves as a liquid when no field is applied; when instead the field is applied the fluid becomes very viscous.

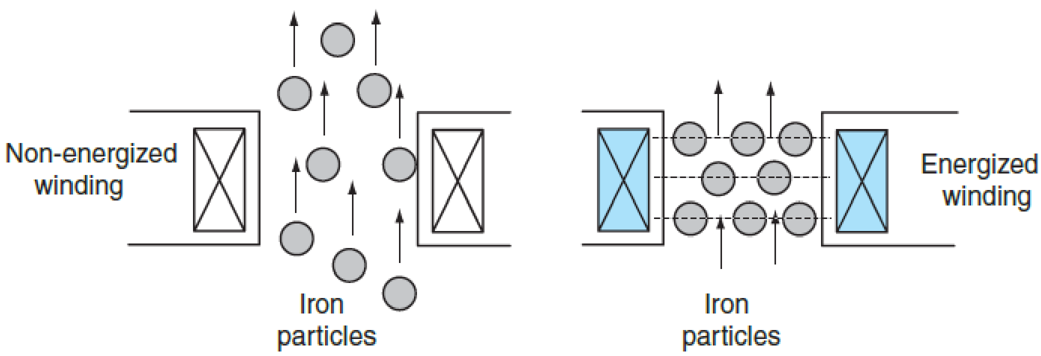

Fig.2 Magnetorheological fluid [2]

1.1.3 Active Suspensions

An active suspension includes actuators that are able to both add and dissipate energy by means of an active force, which is calculated by a control algorithm using data from sensors attached to the vehicle [3]. Unlike semi-active suspension there is an external force to the vehicle body either in upward or downward direction regardless of the absolute vehicle velocity.

1.2 Eddy Current Dampers

Eddy currents (also called Foucault's currents) are loops of electric current generated in a conductive material subjected to a time-varying magnetic flux. According to Lenz's law the direction of the electric current which is induced in a conductor by a changing magnetic field is such that the magnetic field created by the induced current opposes the initial changing magnetic field. “This time-varying magnetic field can be induced either by movement of the conductor in the field or by changing the strength of the magnetic field”[16].“Due to the internal resistance of the conductive material, the eddy currents will be dissipated into heat at the rate of I^2R and the force will disappear. As the eddy currents are dissipated, energy is removed from the system, thus producing a damping effect” [8]. A simple experiment used to demonstrate eddy current damping is performed by dropping a magnet down a conductive tube, it is clear to see that the magnet fall far slower than a non-magnetic material. The reason that the magnet falls slowly is due to eddy currents generated in the conducting tube, which create a viscous force. One of the major applications of eddy current is magnetic braking system [9], nevertheless various applications utilizing eddy currents have been developed, such as lateral vibration control of rotating machinery [10] and vibration isolation in levitation systems [13]. Sodano et al. [11-12] exploited eddy currents damping effect to suppress a cantilever beam's vibration by using a copper conductive plate attached to the beam tip in such a way that the beams motion is in line with the poling axis of a fixed cylindrical permanent magnet as shown in Fig.3

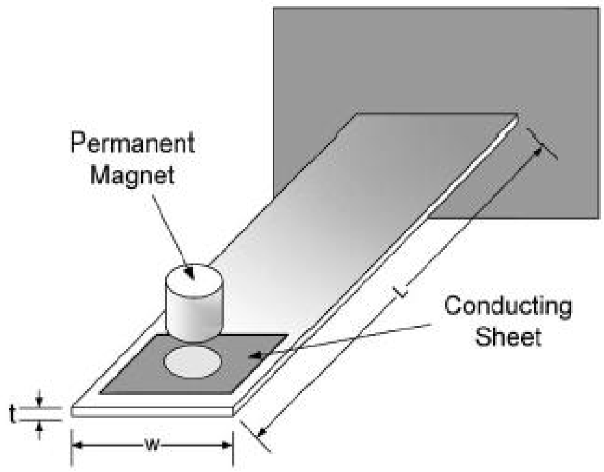

Fig.3 Cantilever beam in magnetic field generated by permanent magnet.

The permanent magnet generates a magnetic field in vertical and horizontal or radial axis that passes through the conducting sheet. Since the deflection of the beam is in the vertical direction and the eddy current depends by the cross product between the velocity of the conductor and the magnetic flux density, Eq.(1.1), the vertical component of the magnetic field does not contribute to the generation of eddy currents.

$$\bar{J} = \sigma(\bar{v} \times \bar{B}) \qquad (1.1)$$

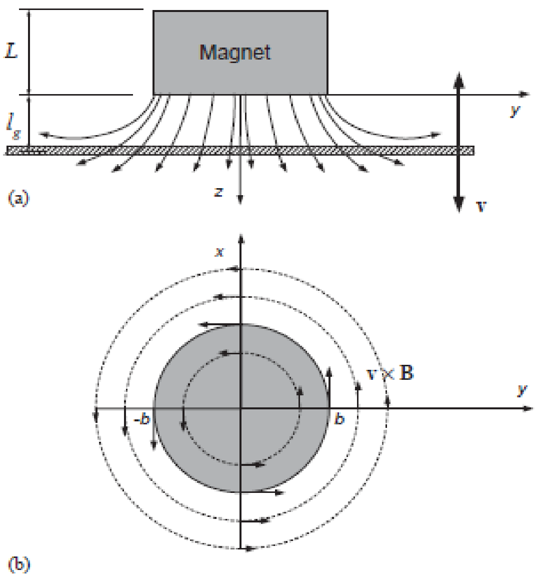

Fig.4 (a) Magnetic field and (b) the eddy currents induced in the cantilever beam

Different from previous eddy current damper with a similar configuration [14],[15] the one proposed by Sodano [11] exploit the radial magnetic flux to generate the electromotive force rather than the axial magnetic flux. In a later study Sodano [12] proposed an improved concept consisting of two magnets positioned on opposite sides of the beam rather than a single magnet and shows that, when using two magnets, the magnetic flux of each magnet is compressed in the poling direction, causing the intensity in the radial direction to be enhanced as shown in Fig.5.

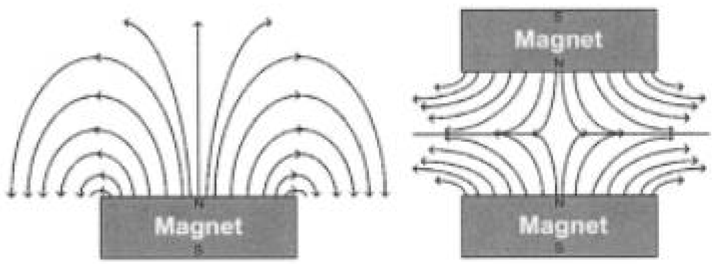

Fig.5 Schematic showing the magnetic flux of one and two magnets

1.3 Ebrahimi's Model

Another application of eddy current can be found in the automotive shock absorber. Ebrahimi [16] introduced a novel magnetic spring damper which consists of a conductor tube and an array of magnetic ring (axially magnetized) separated by iron poles as a mover. The series of annular magnets were assembled onto a non-ferromagnetic rod. The magnets were mounted so they face in opposite directions and there was an iron pole piece between each pairing of magnets. Fig.6. "The eddy current phenomenon occurs either in a steady conductor in a time-varying magnetic field (*transformer* eddy current), or in a conductor that moves in a constant magnetic field (*motional* eddy current)" [16]. Therefore it is possible to write the total induced electromotive force as

$$E = E_{trans} + E_{Motional} = -\int_s \frac{\partial \bar{B}}{\partial t} \cdot d\bar{s} + \oint (\bar{v} \times \bar{B}) \cdot d\bar{l} \quad (1.2)$$

where *v* is the relative velocity of the magnetic flux and conductor and B is the magnetic flux density.

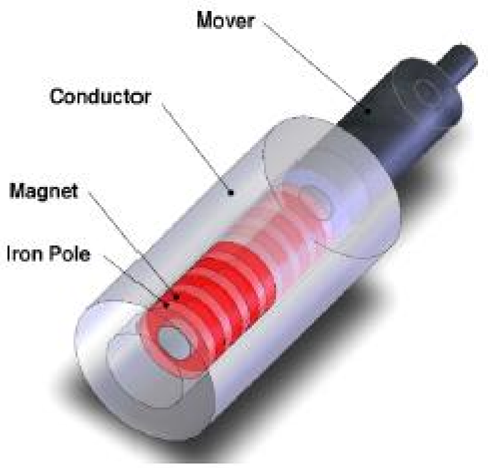

Fig.6 Schematic view of the Ebrahimi damper

In the proposed model the magnetic flux density is constant so we can consider just the motional part of the emf and the induced current density J is given by Eq.(1,1) where σ is the conductivity of the considered conductor. The damping force due to the eddy current is defined by [11]

$$\bar{F} = \int_V \bar{J} \times \bar{B} dV \quad (1.3)$$

where V is the volume of the conductor. If we consider two magnets in the configuration of Fig.7

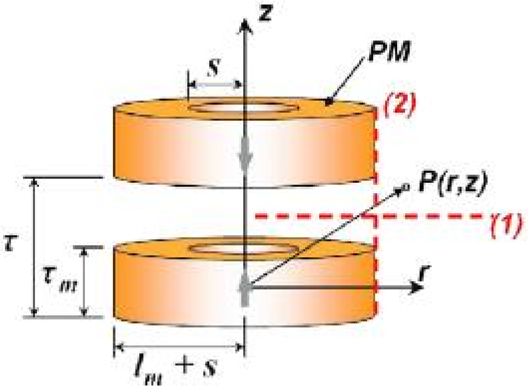

Fig.7 Schematic view of two permanent magnet with like poles in close proximity

we can write that the damping force in the z direction as [16]:

$$F = -\hat{k}\sigma(\tau - \tau_m)v_z \times \int_0^2 \pi \int_{r_{inside}}^{r_{outside}} r B_r^2(r, z_0)\, dr\, d\theta \quad (1.4)$$

where r_{inside} and $r_{outside}$ are the inside radius and outside radius, τ , τ_m and B_r are the pole pitch, the magnets' thickness and the radial component of the magnetic flux density. In a damper, force is proportional to the velocity through a damping coefficient C so to highlight this aspect we can define an equivalent damping coefficient as follows:

$$C = \sigma \int_V B_r^2\, dV \quad (1.5)$$

To find an analytical solution for the magnetic field Ebrahimi proposed the model of Craik [17]. By looking the permanent magnet as a sum of infinite small circular loops, in each of which flows an electric current, the magnetic flux density in a certain point out of the permanent magnets is obtained through the integration of the contribution of each current loop in this specific point. For a permanent magnet with length τ_m and radius R, the magnetic flux density at distance (r,z) from the magnet center is given by :

$$B_r(r,z)\,|_{R,\tau_m} = \frac{\mu_0 I}{2\pi\tau_m} \int_{-\frac{\tau_m}{2}}^{\frac{\tau_m}{2}} \frac{(z-z')}{[(R+r)^2+(z-z')^2]^{\frac{1}{2}}} \times \left[-K(k) + \frac{R^2+r^2+(z-z')^2}{(R-r)^2+(z-z')^2} E(k)\right] dz' \quad (1.6)$$

where $I = M\,\tau_m$ is the equivalent current, *K(k)* and *E(k)* are the complete elliptic integral of the first and second type respectively and are defined as:

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1-k^2\sin^2\theta}} \quad (1.7) \quad \text{and} \quad E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1-k^2\sin^2\theta} \quad (1.8)$$

where

$$k^2 = 4\mathrm{Rr}[(R+r)^2 + (z-z')^2]^{-1} \quad (1.9)$$

Along dashed line 1 the axial magnetic fluxes cancel each other while the two radial components combined together, so the total radial magnetic flux is given by:

$$B_r = 2(B_r(r,z)\,|_{lm+s,\tau_m} - B_r(r,z)\,|_{s,\tau_m}) \quad (1.10)$$

The outward magnetic flux from each pole is estimated by:

$$\phi = 2\pi(l_m + s)(\tau - \tau_m)B_r \quad (1.11)$$

The following table summarizes all the parameters used in the previous equations and the relative data, which are taken from [16].

PARAMETERS	VALUE
Air-gap s_c	0.5 (mm)
Pole pitch τ	24 (mm)
Magnet's thickness τ_m	12 (mm)
Magnet's diameter $2(l_m+s)$	90 (mm)
Magnet's material	NdFeB alloy $B_r = 1.17$ (T)

Table1: Parameters of the magnet assembly

The Eq.1.10 does not have an analytical solution so in this thesis is used a numerical approach with the auxiliary of Matlab program. The reason why Eq.1.10 does not have an analytical solution, is due to the presence of the two elliptic integral E(k) and K(k), which cannot be expressed in terms of elementary functions. An "ad hoc" function, reported in the appendix A, is implemented to calculate the elliptic integrals which are approximated by series of polynomials:

$$K(k) = \frac{\pi}{2}\left(\sum_{n=0}^{\infty}\frac{(2n)!}{2^{2n}(n!)^2}\right)^2 \quad (1.12)$$

$$E(k) = \frac{\pi}{2}\left(\sum_{n=0}^{\infty}\frac{(2n)!}{2^{2n}(n!)^2}\right)^2\frac{k^{2n}}{1-2n} \quad (1.13)$$

Therefore once estimated the value of the elliptic integral we can calculate the outer integral of Eq. 1.10. Among the possible methods of numerical integration that could be used, in this thesis was adopted the Trapezoidal method. The latter consist in partitioning of the integration interval in a large number of domains and for each domain the value of the integral is calculated as the product of the domain by the mean value of the function in that domain.

Chapter 2

Regenerative Suspensions

Despite employing advanced control algorithms and actuators, high energy consumption, complex mechanism, and low reliability still limit the application of the active suspension in practical applications [29]. A conventional shock absorber reduce the vibration trough viscous damping and converts the kinetic energy into heat energy dissipated. Segal and Xiao-pei [6] have demonstrated that the dissipated energy of four dampers of a passenger car traversing a poor road at 13.4 m/s reached approximately 200 W of power. If we can recycle this energy it is possible to achieve a self-powered suspension [4],[5]. The mechanical energy of a vehicle body vibration can be converted into useful electrical energy by using electromagnetic dampers: the vibration energy is converted into electricity via an electric motor (induction machine or DC motor or synchronous machine) and stored in a condenser or battery for further use [7]. Electromagnetic dampers can be either rotational or linear. The former make use of a mechanism, like the one shown in Fig.8, to convert the linear vibrational motion between the body and wheel into the rotating motion of the DC motor which in turns generate electric power; the latter, instead, can directly translate linear motion into electrical energy and vice versa.

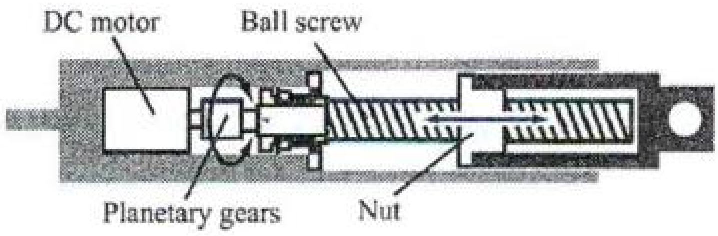

Fig.8 Ball-screw mechanism to convert linear motion into rotational

A linear motor simplify the mechanical design and however it guarantees high motor force to weight ratio, fast response and high precision. The proposed linear motor (Fig.9) is a tubular motor with permanent magnets axially-magnetized, fastened together in a non-magnetic tube, which slides on another tube shielding the stator coil [27]

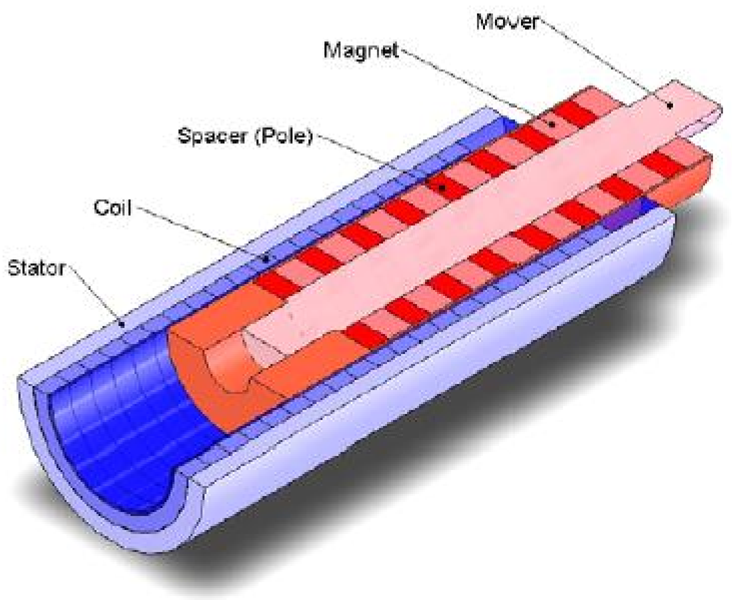

Fig.9 Linear tubular permanent magnet motor

The general configuration of regenerative suspension systems is illustrated in Fig.10

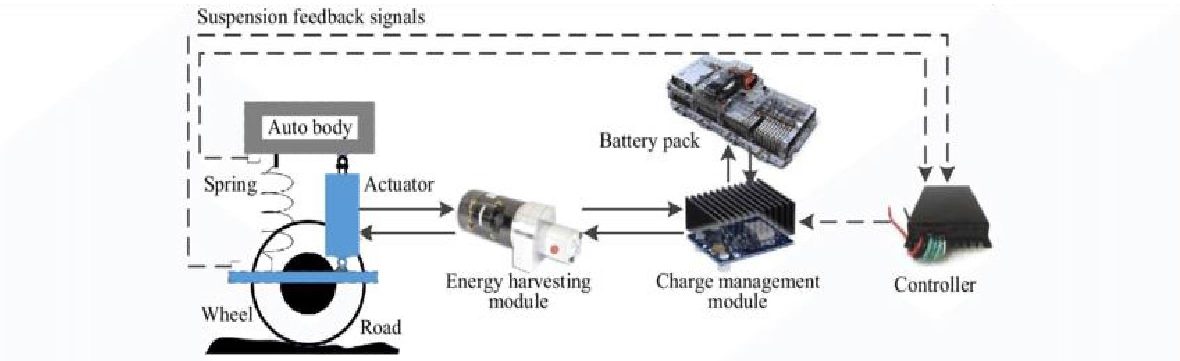

Fig.10 General configuration of regenerative suspension

The regenerative damper (composed by actuator and energy harvesting module) can transform suspension reciprocating mechanical vibration into recoverable electricity. Due to the uneven road profile, the output voltage of above regenerative damper usually fluctuates in a wide range. The charge management is used to narrow the range of fluctuating voltage, thus efficiently charging the battery pack. By collecting the suspension feedback signals, the controller can regulate the charge management module in real time, and improve the ride comfort and fuel efficiency [32].

2.1 Motor constant

The thrust constant of a moving magnet type linear motor is given by Mizuno [31]

$$K_f = \frac{\phi(p+1)N}{\tau}$$

Where Φ is the magnetic flux due to the permanent magnet, p the number of poles, N is the number of turns per coil.

$$\phi = 2\pi(l_m + s)(\tau - \tau_m)B_r$$

When adopting the international system of unit the thrust coefficient is numerically equal to the back electro-motive force coefficient K_e.

2.2 Proposed Self-Powered System

Many authors proposed regenerative system[18]-[22], or focus on saving the energy consumption in active control system[23][24]. However, it is not achieved to realize the system which attains active control only with the regenerated vibration energy. In the following pages it is proposed a practical system [4][5] to achieve self-powered active vibration control by using an actuator connected to a condenser through relay switches which decide the operation mode and a variable resistor which control the amount of electric current. The latter is proportional to the actuator force, so it can be used as the control variable of the system. The proposed system is applied to a two degree of freedom suspension system composed of a primary suspension with a passive damper and a first spring and a secondary suspension with a DC motor installed in parallel with another spring, as in Fig.11

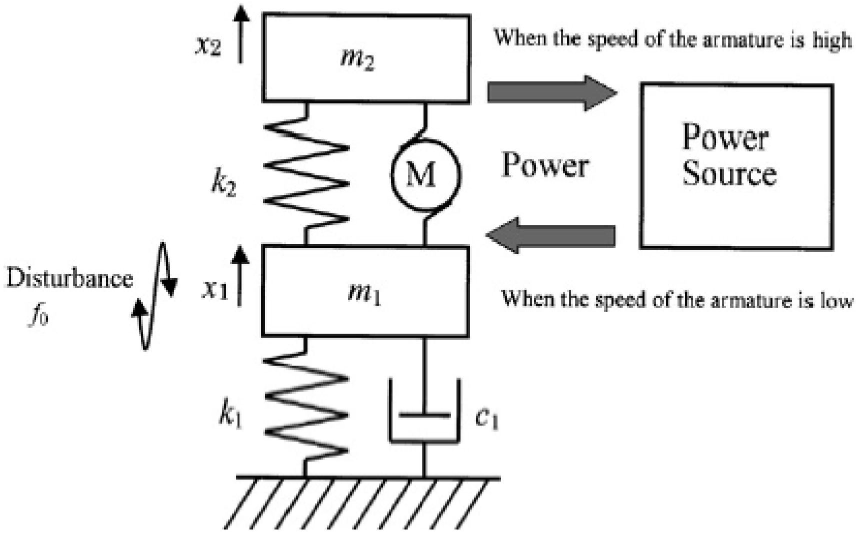

Fig.11 Schematic of the self-powered active vibrations control system

When the speed of the armature is high the DC motor act as a generator and can charge a condenser, if it is to low instead the motor cannot generate energy and consumes the energy stored in the condenser.

2.2.1 Quarter Car Model

A quarter car model like the one showed in Fig 11 is a model that represent only one quarter of the vehicle body. It is constitute by two masses, the sprung and the unsprung mass which are connected with springs and dampers or, in case, actuators. The sprung mass is determined by a quarter of the vehicle mass, including eventual passengers an payloads. The unsprung mass instead is represented by the mass of a tyre, the wheel, the brake, the wheel carrier and part of the suspension system. The tyre is simplified as the parallel of a spring and a damper (denoted by k_1 and c_1 in the figure 11).

2.2.2 Equations Of Motion

The equations of motion of the quarter car model as depicted in Fig.10 are written as follows:

$$\begin{aligned} \ddot{x_2}m_2 + k_2(x_2 - x_1) &= f \\ \ddot{x_1}m_1 + c_1\dot{x_1} - k_2(x_2 - x_1) + k_1x_1 &= f_0 - f \end{aligned} \qquad (2.1)$$

where

m_1, m_2: unsprung and sprung masses

x_1 , x_2 : wheel and body displacement
c_1 : tire damping coefficient
k_1 , k_2 : tire and suspension stiffness
f , f_0: actuator force and road disturbance

2.2.3 Model Of The DC Linear Motor

An ideal linear DC motor can be described by the following relations :

$e_i = -\varphi \dot{z}$ (2.2)

$f = -\varphi i = -\varphi \frac{e_i}{r}$ (2.3)

where
f : actuator force
ż : stroke velocity of the motor
ϕ : motor constant ($K_f = K_e = \varphi$)
e_i : induced voltage
r : resistance of the motor
i : current of the armature

By combining equations (2.2) and (2.3)

$f = -\varphi^2 \frac{e_i}{r}$ (2.4)

The expression of the actuator force has the same form as the one of viscous damping force, so we define c_{eq} as equivalent damping coefficient:

$c_{eq} = \frac{\varphi^2}{r}$ (2.5)

2.2.4 Active Controller

The active controller has to provide the desirable force of the actuator. In this model a Skyhook control low is applied [26]. This controller simulates the behaviour of an imaginary damper connecting the sprung mass to an unmovable wall. The actuator produces a damping force proportional to the absolute velocity of the sprung mass, while a passive damper gives a damping force proportional to its relative velocity. Therefore the actuator output force is obtain as follows:

$$f_{des} = -c_{sky}\dot{x}_2 \quad (2.6)$$

where c_{sky} is the feedback gain of the controller.

2.2.5 Energy Balance Of DC Motor

A DC motor can work as an electromotor or generator. The working state of the motor connected to a power source can be divided into 4 types [25]:

- Electromotor state: Supply voltage is larger than induced voltage and the direction of the two voltages are opposite. The direction of electromagnetic force is the same as that of the motor, which means electromagnetic force contributes to the movement of the motor. Electrical energy is converted to mechanical energy, consuming energy from the power source. The electromotor state is illustrated in Fig.12

- Generator state: the generator state is shown in Fig.13. In this state supply voltage should be smaller than induced voltage and with opposite direction so that armature current (that has the same direction of induced voltage) can flow from generator to the power source. Electromagnetic force is exported in the opposite direction of motion of the motor, and that's because electromagnetic force opposes the motion of the motor. In generator state, the motor converts mechanical energy to electrical energy, charging the power source.

- Regenerative braking state: the electric circuit of regenerative braking state is illustrated in Fig.14. This case can be seen as a particular case of generator state in which the supply voltage is zero. Here also electromagnetic force is exported in the opposite direction of motion of the motor but instead of charging the power source it is used to decelerate the motor until the speed reaches zero.

- Plug braking state: In this state supply voltage as the same direction of induced voltage. The motor converts mechanical energy to electrical energy, and power source supplies energy to the motor in the meantime making the braking effect more effective than that in regenerative braking state. The circuit of this state is shown in Fig.15.

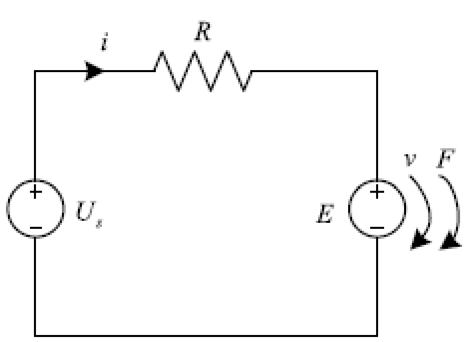

Fig.12 Electromotor state

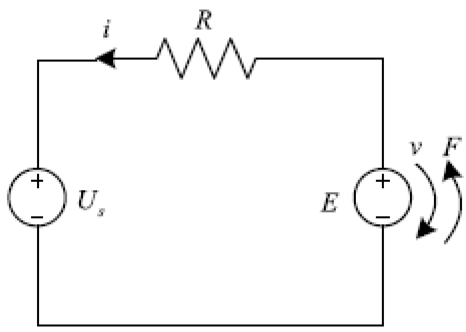

Fig.13 Generator state

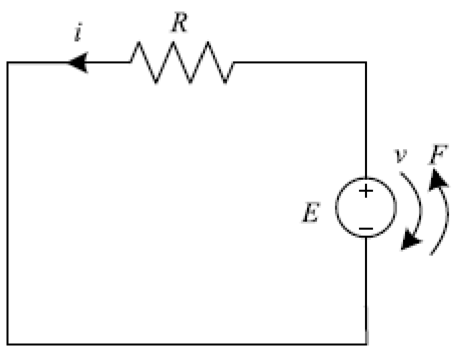

Fig.14 Regenerative braking state

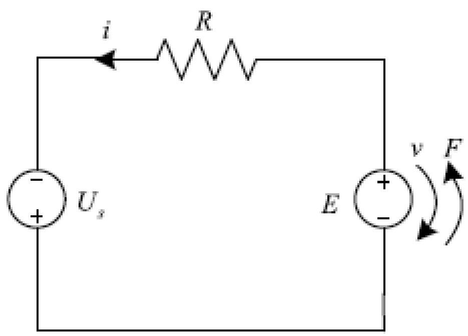

Fig.15 Plug braking state

A simplified armature circuit of the motor is shown in Fig.16. The voltage balance equation can be obtained as:

$e_c = ri + L\frac{di}{dt} + e_i$ (2.7)

Regardless the effect of the inductance, combining Eq.(2.7) ,(2.2) we can write [4]:

$i = \frac{e_c - \varphi\dot{z}}{r}$(2.8) and considering Eq.(12), $f = \varphi\frac{e_c - \varphi\dot{z}}{r}$ (2.9)

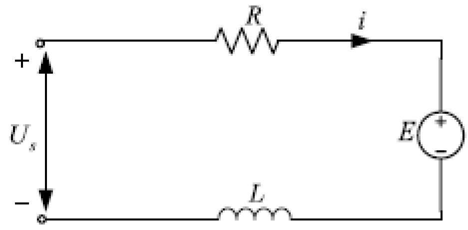

Fig.16 Simplified armature circuit of the motor

From Eq.(2.9) the required voltage and current to obtain the desired force Eq.(2.6) are given by:

$e_c = \frac{r}{\varphi} f_{des} + \varphi \dot{z}$ (2.10) , $i = \frac{f_{des}}{\varphi}$ (2.11)

The power source consumes the power E_c:

$E_c = e_c i = \frac{f_{des}^2}{c_{eq}} + f_{des}\dot{z}$ (2.12)

A "mode variable" Υ, described as follows, is useful to identify three different working mode:

$\gamma = \frac{f_{des}}{-c_{eq}\dot{z}}$ (2.13)

with $\dot{z} \neq 0$. We can rewrite now Eq. 2.12 in terms of Υ:

$E_c = c_{eq}\dot{z}^2\gamma(\gamma - 1)$ (2.14)

The power of the motor can be depicted as:

$M_c = f\dot{z} = -c_{eq}\dot{z}^2\gamma$ (2.15)

For value of Υ between $0< \Upsilon<1$ both M_c and E_c are negative. This means that the actuator takes energy from the suspension and the power source takes energy from the actuator, so we can say that the actuator act as a generator and regenerates vibration energy. Therefore this mode is called "regeneration mode". When $\Upsilon \leq 0$ both M_c and E_c are positive. Now the power source gives energy to the actuator and the latter supplies it to the suspension, so this mode is called "drive mode". Finally when $\Upsilon \geq 1$ E_c is positive while M_c is negative . In this case the actuator takes energy from the suspension and from the power source and dissipates it in the resistance of the armature. Therefore the actuator produces a damping force with the energy provided from the power source. This mode is called "brake mode". Table 1 summarizes these considerations.

Range of Υ	*Power*	*Working mode*	*Description*
$0< \Upsilon<1$	$E_c < 0$ $M_c < 0$	Regeneration mode	The actuator takes energy from the suspension and the power

			source takes energy from the actuator
ϒ≤0	$E_c \geq 0$ $M_c \geq 0$	Drive mode	The power source gives energy to the actuator and the latter supplies it to the suspension
ϒ≥1	$E_c \geq 0$ $M_c \leq 0$	Brake mode	The actuator takes energy from the suspension and from the power source and dissipates it in the resistance of the armature

Table2: Relationship among ϒ, Power and Working mode

2.2.6 Electric Circuit Of The Self-Powered Suspension

A DC motor can work as energy regenerative damper if it is connected to a rectifier and a condenser, or as a viscous damper if it is connected only to a resistance. By controlling the voltage at both end, instead, the DC motor acts as an actuator [30]. The electric circuit of the proposed energy regenerative suspension, shown in Fig.17, can connect the motor in one way or another according to the different working modes decided by the mode variable ϒ. The motor M with its internal resistance R is in series with a variable resistance R_{var} . Two groups of relay switches A and B are utilized to switch among the three working modes. In particular relay switches of group A can connect the motor to the condenser C or to the short-cut circuit; relay switches of group B, instead, change the direction of the controlled current according to the operating zone of the motor.

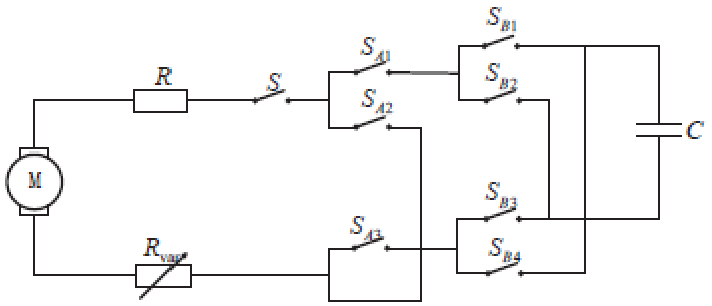

Fig.17 Operating electric circuit of the self-powered suspension

The active controller calculates the desired force, decide the mode and than change the variable resistance, which is related to the electric current and therefore to the force provided by the motor, according to the algorithm illustrated in Fig.18.

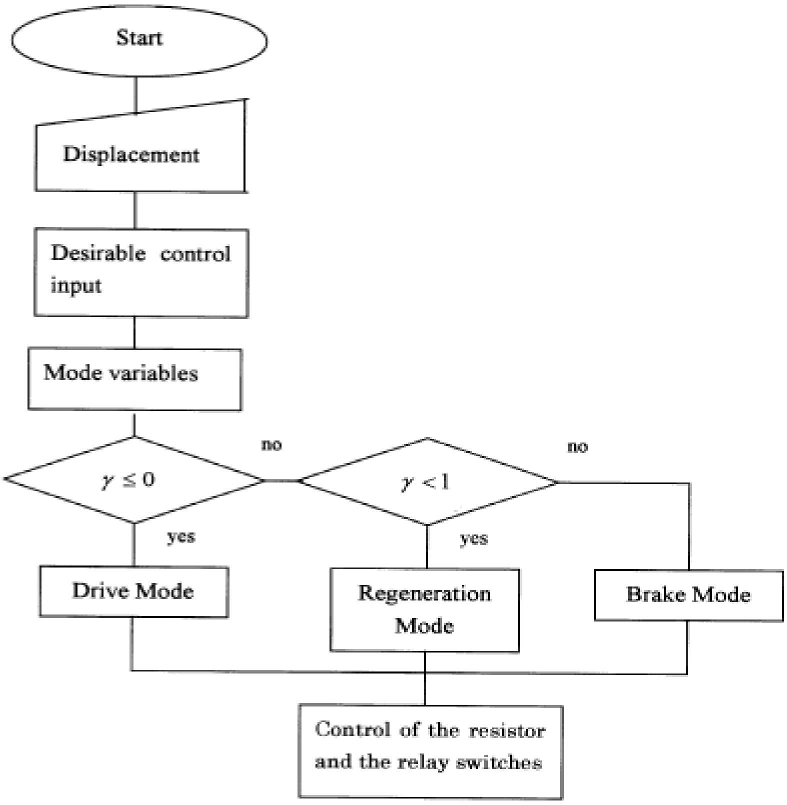

Fig.18 Algorithm of the controller

2.2.7 Regeneration Mode

In regeneration mode the controller charges the condenser which supply the actuator that produces the control force. This force is given by:

$$f = \varphi \frac{\sigma e_c - \varphi \dot{z}}{r + r_{var}} \qquad (2.16)$$

where σ is defined as follows:

$$\begin{aligned} \sigma &= 1(\dot{z} \geqslant 0) \\ \sigma &= -1(\dot{z} < 0) \end{aligned} \qquad (2.17)$$

Through modifying R_{var} it is possible to track the desired control force, so we can calculate the resistance of the variable resistor by replacing f_{des} in Eq.2.16:

$$r_{var} = \left| \frac{\varphi}{f_{des}} (\sigma e_c - \varphi \dot{z}) \right| - r \qquad (2.18)$$

If R_{var} became less than zero, the motor cannot provide the desired force, so it is shorted from the condenser by closing switches S and S_{A2} and act as a viscous damper. The circuits of both cases $R_{var} \geq 0$ and $R_{var} < 0$ when $\dot{z} > 0$ are shown in Fig.19 and Fig.20. When $\dot{z} \leq 0$ S_{B2} and S_{B4} are closed so the actuator is connected to the condenser in the opposite direction. According to the circuit of Fig.20, now the control force is calculated as:

$$f = \frac{-\varphi^2 \dot{z}}{r + r_{var}} \qquad (2.19)$$

Consequently

$$r_{var} = \left| \frac{-\varphi^2 \dot{z}}{f_{des}} \right| - r \qquad (2.20)$$

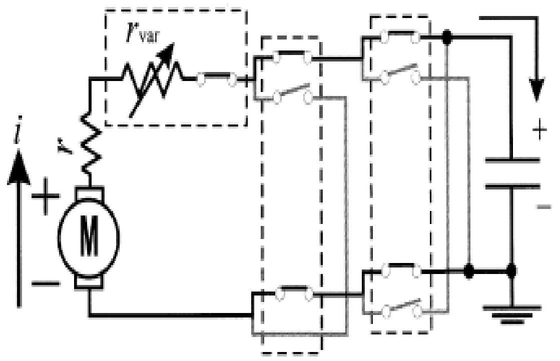

Fig.19 Circuit in regeneration mode with $R_{var} \geq 0$

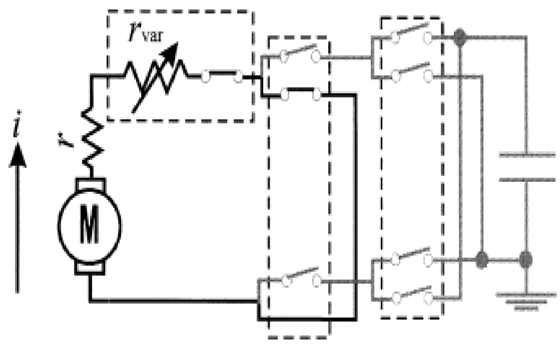

Fig.20 Circuit in regeneration mode with $R_{var} < 0$

2.2.8 Drive Mode

In the drive mode the energy stored in the condenser is utilized to supply the motor which produces a negative damping force. The output of the actuator is the same as in Eq.2.16 and therefore the variable resistance is obtained in the same way Eq.2.18.

$f = \varphi \frac{\sigma e_c - \varphi \dot{z}}{r + r_{var}}$ $\qquad$ $r_{var} = \left| \frac{\varphi}{f_{des}} (\sigma e_c - \varphi \dot{z}) \right| - r$

When R_{var} is negative the controller assign zero value to the resistance. In case $e_c \geqslant \varphi|\dot{z}|$, $R \geq 0$ the controllable switches S, S_{A1}, S_{A3} are closed, then if $\dot{z} > 0$ switches S_{B1}, S_{B3} are also closed (Fig.21) if instead $\dot{z} < 0$ S_{B2} and S_{B4} close instead. When $e_c < \varphi|\dot{z}|$the electric current flows from the actuator to the condenser, to prevent this situation open switch S to cut the circuit (Fig.22)

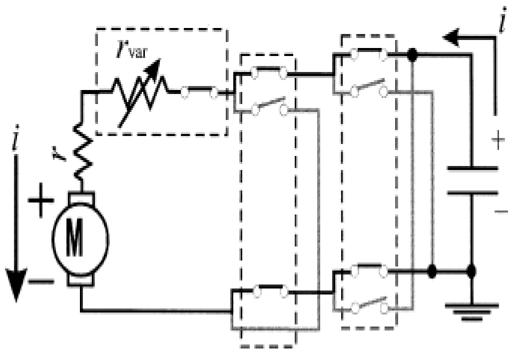

Fig.21 Circuit in drive mode with $e_c \geq 0$

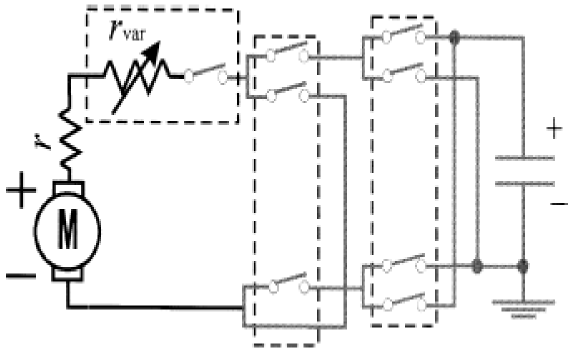

Fig.22 Circuit in drive mode with $e_c < 0$

2.2.9 Brake Mode

During brake mode the actuator produces a large damping force using the energy accumulated in the condenser. We can write the output of the actuator as follows:

$$f = \varphi \frac{-\sigma e_c - \varphi \dot{z}}{r + r_{var}} \qquad (2.21)$$

As already done previously it is possible to calculate R_{var} to obtain the desired force f_{des} :

$$r_{var} = \left| \frac{\varphi}{f_{des}} (-\sigma e_c - \varphi \dot{z}) \right| - r \qquad (2.22)$$

When R_{var} is negative the controller assign zero value to the variable resistance. Furthermore the system disconnect the capacitor when its voltage is less than a certain threshold e_{min} to avoid a reverse voltage will be applied to it. In case $e_c < e_{min}$ the output of the actuator is given by:

$$f = \frac{-\varphi^2 \dot{z}}{r} \qquad (2.23)$$

The circuit for both cases are shown in Fig.23 and Fig 24

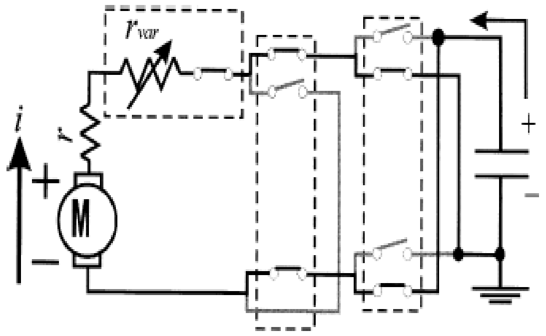

Fig.23 Circuit in brake mode with $e_c \geq e_{min}$

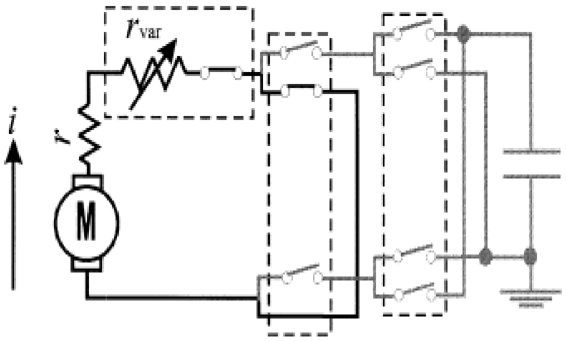

Fig.24 Circuit in brake mode with $e_c < e_{min}$

Chapter 3

Simulation and Results

3.1 Simulink Model

The Simulink model of the self-powered suspension system discussed above is reported here:

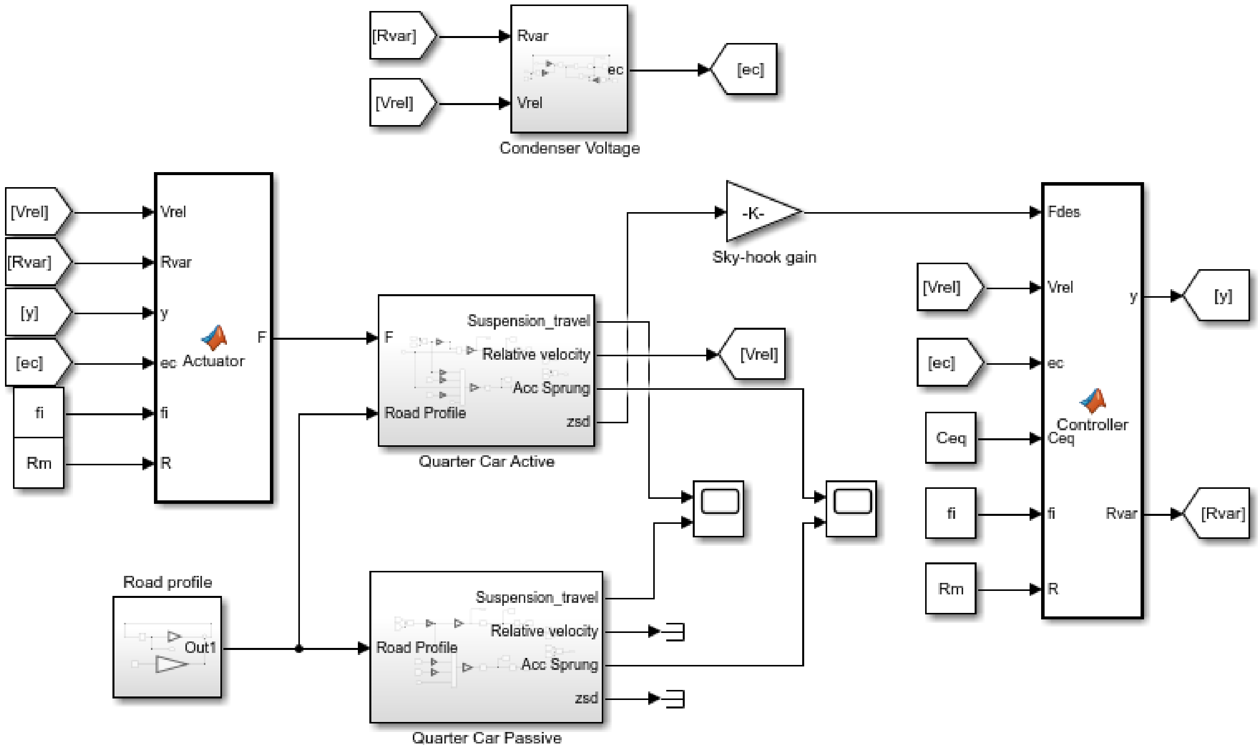

Fig.25 Simulink scheme of the self-powered suspension

Simulations are conducted under random road excitation in the form of white noise. The quarter car active model receives as input the road profile and the actuator force. The latter is provided by a function block (Actuator block), which simulates the relay switches operations according to the mode variable and the variable resistance calculated by another function (Controller block).

Moreover take as input the voltage of the condenser, calculated in the block Condenser Voltage, which is fed back into the controller. The controller decide the mode and the variable resistance based on the condenser voltage,the relative velocity (between sprung and unsprung masses) and the desired force calculated by a sky-hook gain applied to the sprung mass.

3.2 Road Profile

According to Zhang [28] the road input $\dot{z}_r$ can be simulated by a filtered white noise that can be expressed as follows:

$$\dot{z_r} = -2\pi f_0 z_r + 2\pi n_0 w \sqrt{G_q(n_0)v} \qquad (3.1)$$

The parameters of $\dot{z}_r$ are shown below:

PARAMETERS	VALUE	DESCRIPTION
f_0	0.1 Hz	Cut off frequency
n_0	0.1 m^{-1}	Spatial frequency
$G_q(n_0)$	6.4 x 10^{-5} m^3	Road roughness coefficient
v	20 m/s	Vehicle velocity

Table3: Parameters of the filtered white noise

3.3 Quarter Car Model

The quarter car model represented by Eq.2.1, Fig.10 is then implemented. It is reported the scheme of the subsystem called “Quarter Car Active” which takes as input the road profile and the force provided by the actuator and gives as output the following: relative velocity between sprung and unsprung mass, sprung mass acceleration, suspension travel and relative velocity. The last two output are taken as the variables responsible for road holding and ride comfort respectively, therefore are compared with those coming out from “Quarter Car Passive”.

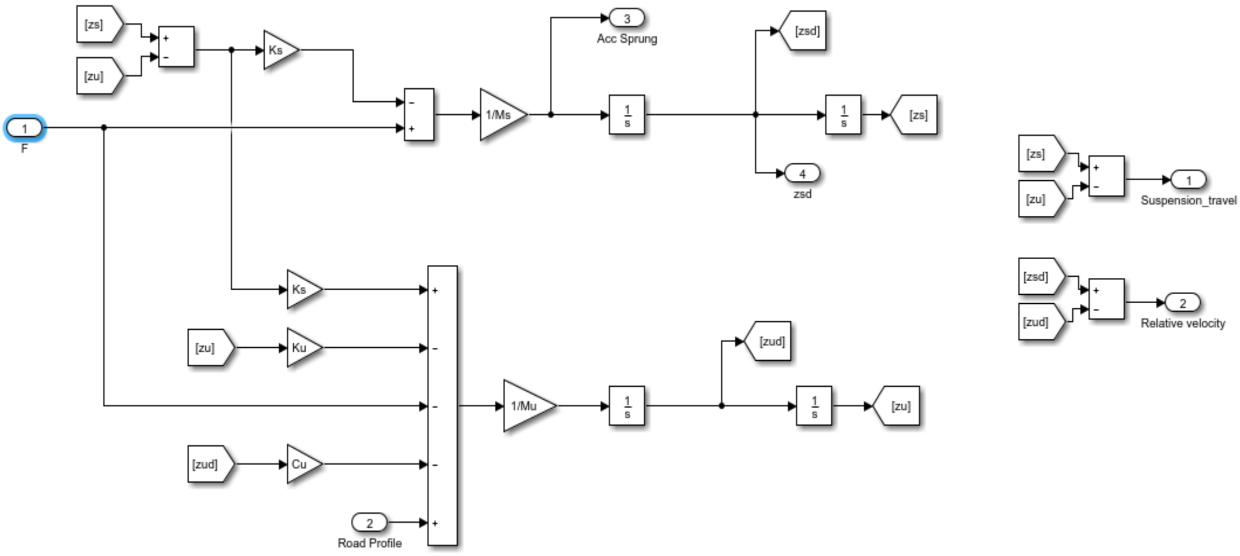

Fig.26 Simulink scheme of the quarter car model

3.4 Sky-hook Damping

The Sky-hook control strategy as described in section 2.2.4 is applied. The gain C_{sky} is chosen with trial and error procedure in order to achieve the best trade-off between C_{sky} and the condenser capacity. In particular the sky-hook damping and consequently the desired force is limited by the voltage of the power source and thus by the capacity of the condenser. On the other hand with a large value of the capacity the condenser voltage may became larger than that of induced voltage, therefore it becomes impossible to transfer the regenerated vibration energy to the condenser.

3.5 Controller

The function implemented in the controller block (reported in the appendix B), taking as input the desired force and relative velocity, calculates the mode variable Υ and variable resistance R_{var} according to the algorithm illustrated in Fig.18. First of all it calculates the desired variable resistance for the regeneration mode (which is the same of that in drive mode) and for the brake mode, than if we are in regeneration mode and the desired R_{var} is negative so it is recalculated according to the new circuit Fig.20, otherwise if the mode is brake or drive and R_{var} is negative than it is set to zero.

3.6 Condenser voltage

The subsystem named as condenser voltage simulates the charging and discharging of the condenser. A high voltage interferes with energy regeneration, while a low voltage makes for incomplete actuator output. The value of the capacity C is chosen with trial and error procedure and is set to 0.01 F. The condenser law is given by:

$$i = C\frac{de_c}{dt} \quad (3.2)$$

By combining eq. (2.29) with (3.2) the following simulink scheme is obtained

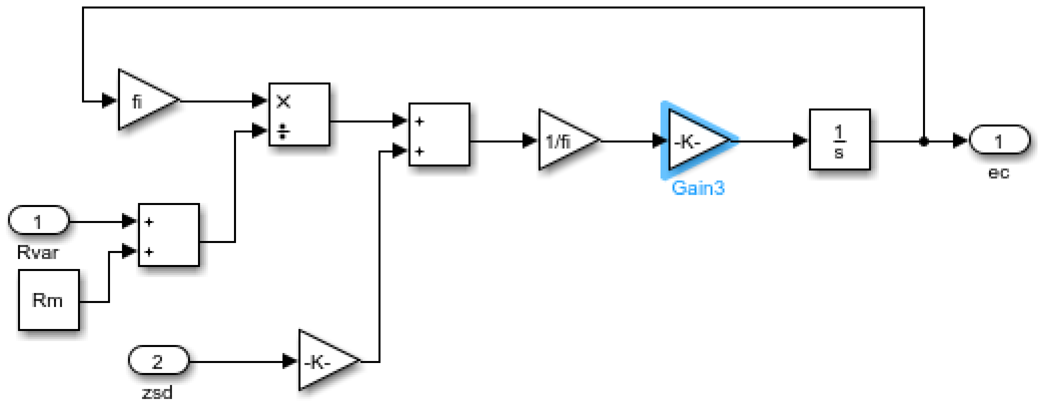

Fig.27 Simulink scheme of the condenser voltage equation

3.7 Actuator

According to the equations of the output force described in the previous chapter a function (reported in the appendix B) is implemented in the Actuator block. The function gives as output the expression of the actuator force taking into account the circuit variations for the various mode. The value of the variable resistance is taken from the controller block as well as the mode variable, while the voltage of the condenser comes from block described above.

3.8 Test and Results

To evaluate the performance of a suspension, as already discussed above, we must take into account two parameters: the suspension travel (the relative displacement between the sprung and the unsprung mass) and the sprung mass acceleration. In Fig.28 and 29 there is a comparison between these parameters for a quarter car passive model (blue line) and for the regenerative one (yellow line).

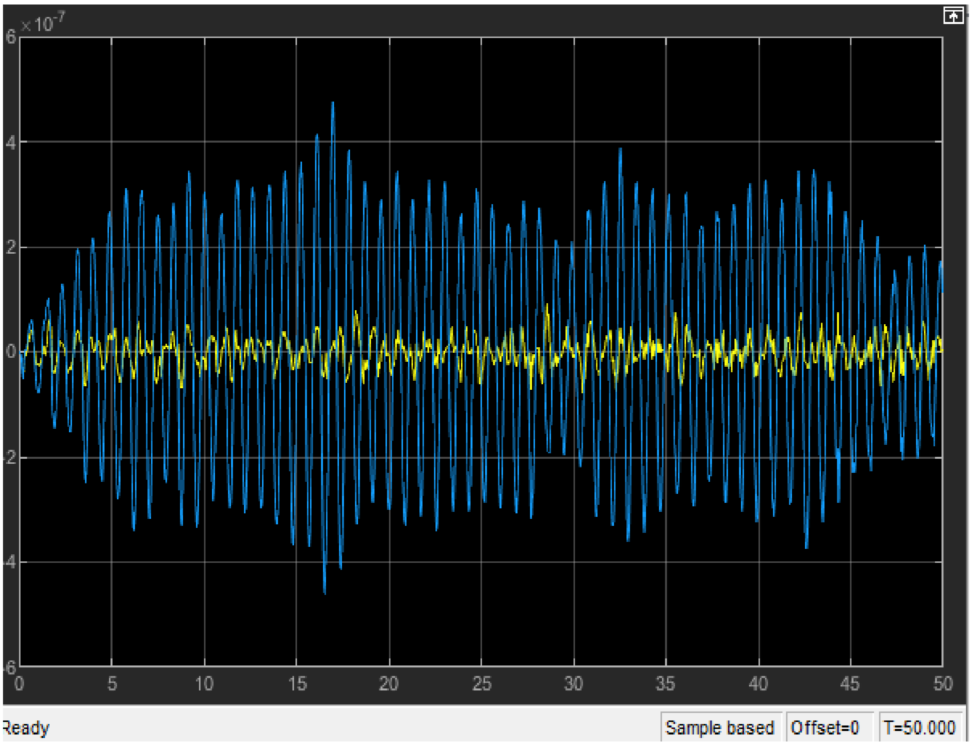

Fig.28 Suspension travel comparison between passive and regenerative model

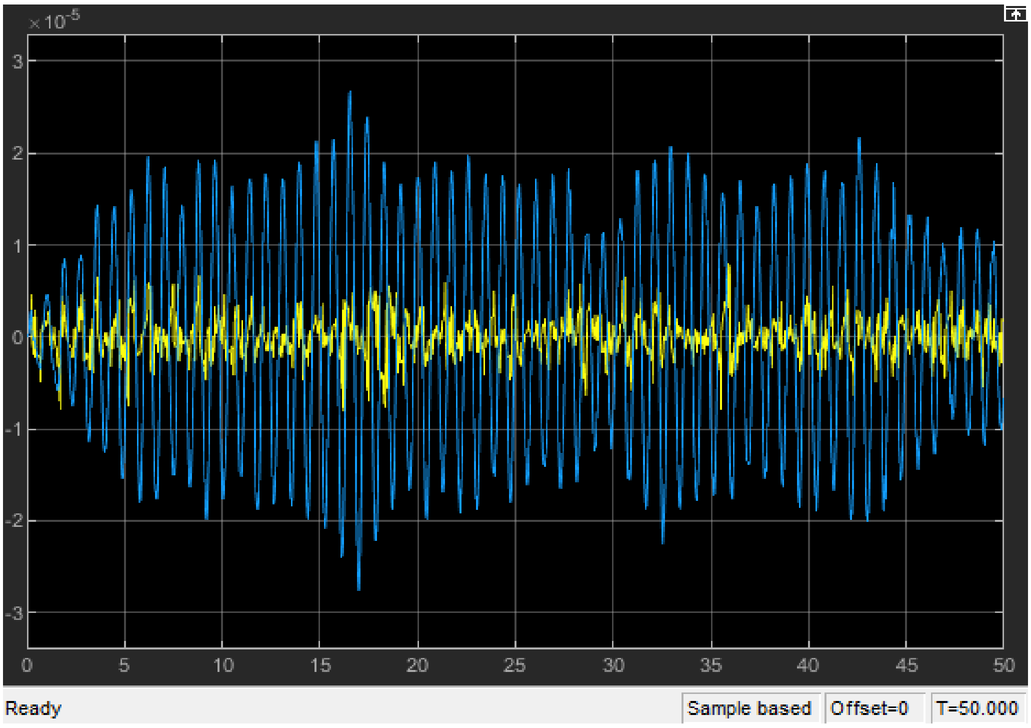

Fig.29 Sprung acceleration comparison between passive and regenerative model

As we can notice both signals are significantly reduced in the case of regenerative model. The comparison between di desired force (yellow) and the actual output of the actuator (blue) is also shown below.

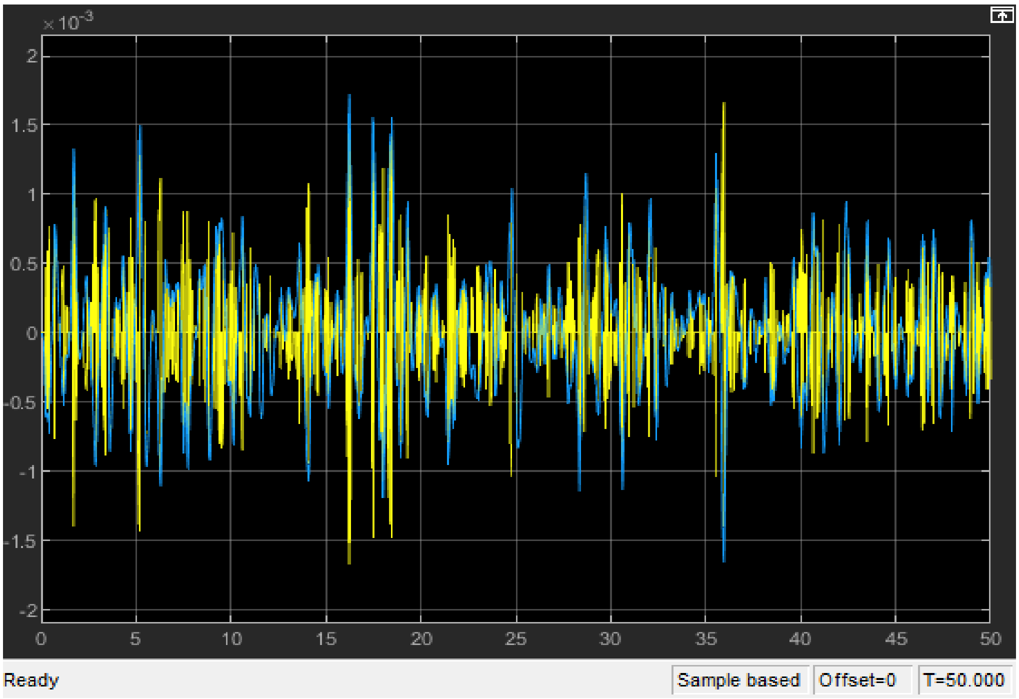

Fig.30 Comparison between desired sky-hook (yellow) force and output force (blue)

Appendix A

Main

```
clear all
close all
clc

global Tm Bresidual

t=20; %simulation time

Rm = 4.7;    %armature resistance

T = 24;        %pole pitch
Tm = 12;       %magnet thickness
Re = 45;    %external radius of the magnet
Ri = 5;    %internal radius of the magnet
Ag = 0.5;     %air gap
M = 1.03e6;   %magnetization
mu = 4e-7*pi; %magnetic permeability
Bresidual = mu*M;
p=12;     %number of poles
Nc = 230; %number of coils

% quarter car parameters
Ms = 290;    %sprung mass
Mu = 59;     %unsprung mass
Ks = 16812;  %suspension stiffness
Cu = 1000;   % damping coefficient of the tire
Ku = 190000; % tire stiffness

G = 2.56e-4; v = 20; n0=0.1; f0=0.1; %parameter white filtered noise
c = 0.1; %capacity of the condenser

passo = 0.1;
nz = (Tm+T-(-Tm/2))/passo;
z = -Tm/2:passo:Tm+T;
```

```
for i = 0:nr
    loading = nz+nr-i
    B = 2*(integralz1B(r(i+1),T/2,Re)-integralz1B(r(i+1),T/2,Ri));
    Br(i+1)=B;
    F(i+1)=4*r(i+1)*(B)*(B)
end
FI=trapz(r,F); %damping force

Phi = 2*pi*Re*(T-Tm)*B %magnetic flux
fi = sqrt(Phi*(p+1)*Nc/T) %Thrust coefficient
Ceq = (fi^2)/Rm    %Equivalent damping

for i=0:nz
    loading = nz-i
    Bz1=integralz1B((Re+Ag),z(i+1),Re)-integralz1B((Re+Ag),z(i+1),Ri);
    Bz2=integralz1B((Re+Ag),(T-z(i+1)),Re)-integralz1B((Re+Ag),(T-z(i+1)),Ri)
    Bz(i+1)=Bz1+Bz2;
end

figure (1)
plot(r,Br,'b','linewidth',1.6)
grid on
hold on
ylabel('Radial Flux Density (T)','FontSize',13)
xlabel('R - Position (mm)','FontSize',13)
title('Br - Radial sweep','FontSize',13)

figure (2)
plot(z,Bz,'b','linewidth',1.6)
grid on
xlim([(-Tm/2) (T+(Tm/2))])
ylim([-0.6 0.8])
ylabel('Radial Flux Density (T)','FontSize',13)
xlabel('Z - Position (mm)','FontSize',13)
title('Br - Axial sweep','FontSize',13)
```

Magnetic Field Function

```
function [Br]=integralz1B(r,z,R)
global Tm Bresidual
passo = 0.03;
n = Tm/passo;
z1 = -Tm/2:passo:Tm/2;

for i=0:n
    bb=funcB(r,z,z1(i+1),R);
    b(i+1)=bb;
end
Br = (Bresidual/(2*pi))*trapz(z1,b);
end

function [B]=funcB(r,z,z1,R)

k=((4*R*r)/((R+r)*(R+r)+(z-z1)*(z-z1)))^(1/2);

ntot=50;
for n=0:ntot
    a1=factorial(2*n);
    a2=factorial(n);
    a3=2^(2*n);
    b=(a1/(a3*a2*a2))^2;
    celulaK=b*(k^(2*n));
    celulaE=celulaK/(1-2*n);
    matrixK(n+1)=celulaK;
    matrixE(n+1)=celulaE;
end
cK=sum(matrixK);
cE=sum(matrixE);
K=(pi/2)*cK;
E=(pi/2)*cE;

B = ((z-z1)/(r*((R+r)^2+(z-z1)^2)^0.5))*(-K+E*((R^2+r^2+(z-z1)^2)/((R-r)^2+(z-z1)^2)));

end
```

Appendix B

Controller Function

```
function [y,Rvar] = Controller(Fdes, Vrel, ec, Ceq, fi, R)
Rvar = 0;
if Vrel == 0
    y=0;
else
y = Fdes/(-Ceq*Vrel);

if Vrel>=0
    sigma = 1;
else
    sigma = -1;
end
% Mode variable
if y<1  % Drive mode/Regeneration mode
    Rvar = abs(fi/Fdes*(sigma*ec-fi*Vrel))-R;
elseif y>=1  % Brake mode
    Rvar = abs(fi/Fdes*(-sigma*ec-fi*Vrel))-R;
     if (abs(fi*(sigma*ec-fi*Vrel))-abs(Fdes)*R)<0
         if(y>0 && y<1)
        Rvar = abs((-fi^2)*Vrel/Fdes)-R;
         else
        Rvar = 0;
         end
    end
end
end
```

Actuator Function

```
function F = Motor(Vrel,Rvar,y,ec,fi,R)
if Vrel>=0
    sigma = 1;
else
    sigma = -1;
end

if (y>0 && y<1)
    if Rvar>=0
        F = (fi*sigma*ec-fi*Vrel)/(R+Rvar);
    else
        F = (-fi^2)*Vrel/(R+Rvar);
    end

elseif y<=0
    if ec>=fi*abs(Vrel)
        F = (fi*sigma*ec-fi*Vrel)/(R+Rvar);
    else
        F = 0;
    end

else
    F = (fi*(-sigma)*ec-fi*Vrel)/(R+Rvar);
end
```

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