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Bond Graph modeling of automotive suspension system using a linear actuator

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Abstract— This paper presents dynamic modeling of automotive suspension using the graphical approach: Bond Graph. The advantage of this active technology is the generation of the desired force acting between the unsprung wheel mass and the sprung vehicle body mass using a tubular permanent magnet linear synchronous actuator (TPMLSA).

The dynamic suspension actuated by the TPMLSA is modeled by Bond Graph formalism. The simulation of this system is done under the software environment 20-SIM that is specific to Bond Graphs. The results of this study allow the evaluation of the suspension performance in terms of comfort and safety and effectiveness of the bond graph modeling.

Index Terms—active suspension, bond graph, TPMLSA, dynamic, modeling; simulation.

◆

1 INTRODUCTION

Currently, the suspension of the vehicle is the subject of many research scientific literatures and automotive industries. To meet the user requirements, the automotive industry develops a new suspension technology called active suspension [1]. This system has the performance to generate force using an active source that can be either hydraulic or pneumatic actuator [2].

Over the last ten years, the evolution of power electronics, permanent magnetic materials and electronic control systems has brought development of active suspension motorized by TPMLSA.

The integration of TPMLSA in active suspension system is justified by the following criteria [3]:

1. Vehicle weight optimization that causes the reduction of costs.
2. Minimization of wheel vibration problems.
3. Improvement of driving dynamics and stability.
4. Suspension energy recovery.

The dynamic modeling behavior of the quarter suspension system is complex because of the heterogeneousity of the systems (electrical, mechanical and electronic). These systems do not have the same communication language. For this reason, the choice of the modeling approach rested on the graphical tool Bond Graph (BG) for the representation of models and control laws.

This paper is organized as follows: Part II presents a state of art on the existing technologies in automobile suspension, as well as their advantages and disadvantages. Part III is intended into the description of the active suspension using a TPMLS actuator. Part IV is the setting in equation of the dynamic model of the active suspension and the actuator. Part V presents the proposed modeling approach which is based on the application of the BG tool to the active suspension. Part VI presents the simulation results of the dynamic behavior of the quarter suspension system that are simulated under by 20-SIM software.

2 AUTOMOTIVE SUSPENSION

In this section, a description of principal functionalities of automotive suspension, also their classification.

2.1 Function of Automotive Suspension

In vehicle, the suspension is a system that links the unsprung mass (wheel) at the mass sprung (chassis). Indeed, the main functions of the suspension are [4]:

1. The transfer of force between the vehicle and the road.
2. The good performance of the road, maintaining a permanent contact between wheels and ground.
3. The oscillation filtering of the wheel ensures passenger comfort and protection of mechanical parts.

2.2 Classification of the Automotive Suspension

In the literature, the suspension techniques are divided into three categories:

Passive suspension [5]: it is widely used because of its low cost. Its mechanical structure is simple because it is composed by two passive elements: one is a spring; the other is a damper fixed value.

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(This information is optional; change it according to your need.)

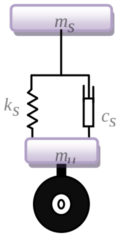
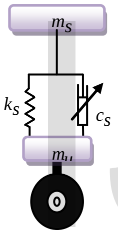
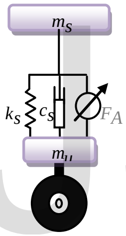
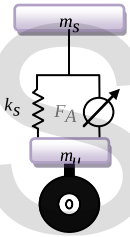
These elements serve firstly to isolate the chassis of the vehicle against vibrations due to the road. Secondly they allow maximizing the contact with the ground. However, their performances are limited

Semi-active suspension [6]: is composed by a spring stiffness and a variable damper. The advantage of this technology comes down to the low power consumption of energy. However, these capabilities are limited due to dissipation of energy.

Active suspension: is composed by a mechanical spring in parallel with an actuator to create the necessary forces. It is widely studied in the automotive industry because of its ability to improve the ride quality and road handling [7]. To this criterion is added, the ability to minimize the acceleration of the vehicle body and the suspension deformation. That improves braking and traction control of the vehicle [8].

The Physical models for various categories of automotive suspension presented above are illustrated in Table I.

TABLE 1
CATEGORIES OF AUTOMOTIVE SUSPENSIONS [9].

Suspension	***Passive***	***Semi-active***	***Active (hydraulic)***	***Active (electric)***
Physical model				
Components	Spring with damper	Spring with variable damper	Spring, damper with a hydraulic actuator	Spring with a electric actuator

3 ACTIVE SUSPENSION DESCRIPTION

The active suspension system actuated by the TPMLSA is the principal object on this paper. In order to describe this system, we present its physical modeling, its control system and the correspondent TPLMSA.

3.1 Physical Modeling

The physical model of the quarter suspension active is given by Fig.1. This model allows the sizing of the whole vertical chassis-wheel-tire.

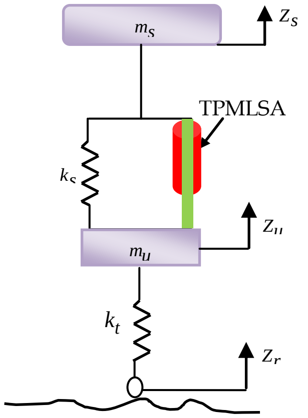


Fig. 1. Physical model of active suspension.

This model consists on two distinct masses: one is the unsprung mass (tire and wheel). The second is the sprung mass (chassis). The wheel is modeled by a linear spring characterized by a constant k_t. The shock absorber of the wheel is considered negligible. As regards, the suspension is composed of two components: one is a spring and the other is a linear actuator. This actuator applies a force F_A between the unsprung and sprung masses [10].

3.2 Suspension Control System

The block diagram of the active suspension function is shown in Fig. 2. It is composed of: a battery, a power converter, an actuator (TPMLS) and sensors.

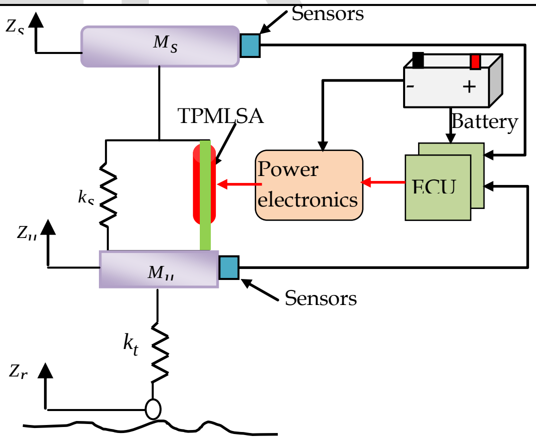


Fig. 2. Block Digram of the active suspension.

Sensors are placed at the wheel and suspension to measure the road profile and the vehicular response variables. These parameters will be transmitted to the Electronic Control Unit (ECU), which, data and computes the reference force level. The actuator is powered by external sources and generates the necessary absorbing (damping) forces. Fig. 3 summarizes the suspension control system.

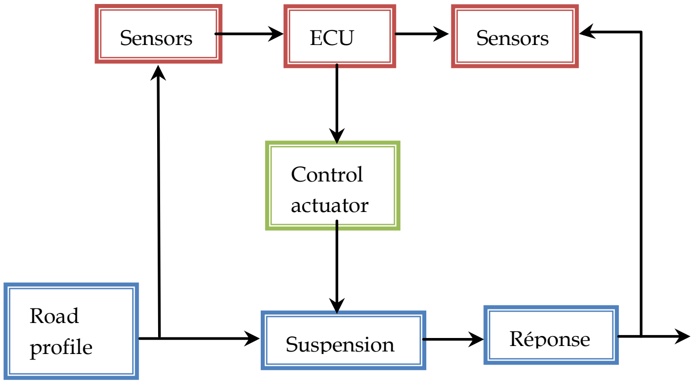


Fig. 3. Suspension control system.

3.3 Presentation of the TPMLS actuator

In the literature there are many machine topologies which might be employed in automotive active suspension applications like linear and rotary brushless. In this work the TPMLS actuator is used thanks to their high massive force.
The principal advantage of integration of this actuator in the automotive suspension is that it directly converts electrical energy into mechanical energy, that is, a usable mechanical force and motion.

Some advantages of TPMLSA, like: high dynamics thanks to the reducing of mass, improved positioning accuracy, so less friction and noise and better reliability [10], [11].

4 QUARTER MODEL OF THE ACTIVE SUSPENSION SYSTEM

The vertical dynamic behavior of quarter model is described by the active suspension model and its actuator.

4.1 Active Suspension Model

The equation of motion can be described as following:

$$m_s \ddot{z}_s = -k_s\left(z_s - z_u\right) + F_A - F_f \qquad (1)$$

$$m_u \ddot{z}_u = k_s\left(z_s - z_u\right) - k_t\left(z_u - z_r\right) - F_A + F_f \qquad (2)$$

4.2 Actuator Model

To establish the TPMLSA model, simplifying assumptions are considered: unsaturated magnetic circuit, the Foucault current, hysteresis and skin effect are neglected [12]. The model of the actuator is described in the PARK frame.
The electric model of the actuator is given by equations (3) and (4).

$$\begin{cases} V_d = R_d\, i_d + \dfrac{d\psi_d}{dt} - N_p\, v \psi_q \\ V_q = R_q\, i_q + \dfrac{d\psi_q}{dt} + N_p\, v \psi_d \end{cases} \qquad (3)$$

With: $N_p = \dfrac{\pi}{\tau_p}$ (4)

The two linkage flux expressions in the PARK frame are given by:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \qquad (5)$$

$$\text{with : } \psi_f = \sqrt{\frac{3}{2}}\,\hat{\phi}_f \qquad (6)$$

The expression of the electromagnetic force is given by the following equation:

$$F_A = N_p\left[\psi_f + \left(L_d - L_q\right) i_d\right] i_q \qquad (7)$$

The mechanical model is presented by:

$$F_A = F_d + B\,v + M\frac{dv}{dt} + f_s\, sign(v) \qquad (8)$$

All the notations are presented in Table V.

5 DYNAMIC MODELING OF THE ACTIVE SUSPENSION SYSTEM

The modeling of active suspension dynamic behavior is done with the BG tool based on energy exchange. In the following section, a state of art about the BG tool and its application on the active suspension system is presented.

5.1 Presentation of the BG Tool

The active suspension system is a mechatronic system involving heterogeneous subsystems and combining the engineering synergy. The modeling of such complex system requires a graphics approach like BG one.

The BG tool is a graphical modeling tool that covers all physical systems (electronic, mechanical, hydraulic, thermal ...) regardless of class system represents (linear, nonlinear, continuous, discrete samples). It is based on the idea of the energy transmission between subsystems. The bond graph systematically combines two variables nature: effort and flow [13].

The BG is divided into four main categories of elements: the active elements, passive elements, power conserving elements and detectors.

1. The active elements represent sources of effort S_e and flow S_f. These elements provide input power to the system.
2. The passive element is classified in two categories. The

first is dissipated energies (resistive element R). The second is stored energies (capacitance C and tia I elements).

3. Power conserving elements are composed by: flow conservation junction '0', effort conservation junction '1', transformer *TF*, and gyrator *GY* elements.
4. D_e and D_f represent respectevely the effort and flow sensors. They are supposed to be perfect, so no power consuming.

The BG elements are illustrated in Fig. 4.

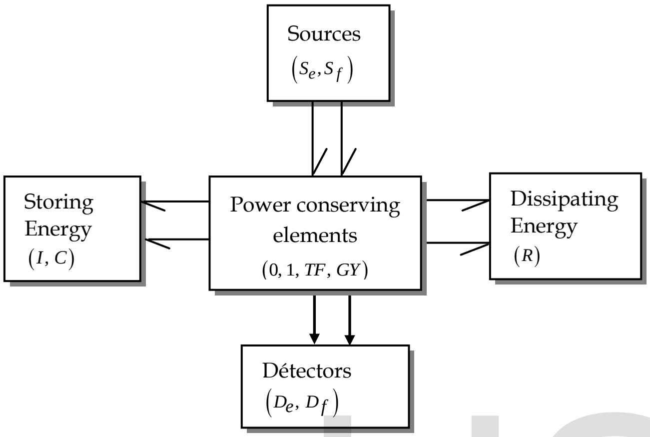


Fig. 4. BG elements.

Choosing the BG approach is justified by some advantages, like [14]:

1. It as a multidisciplinary and unified graphical modelling language.
2. Its causal properties and graphical aspect.
3. The BG subject of fast evolution and it can be refined by adding graphically many elements such as loss thermal inertia and the storage effects without needing to start the work from the begin [15].
4. The BG is a performed approach used not only to model and simulate the mechatronic systems. But also it can be an excellent support for analysis, synthesis and diagnostics.

5.2 Application of BG Tool for Active Suspension Modeling

The BG model of active suspension is established in accordance with equations (1) and (2) and presented with Fig. 5.

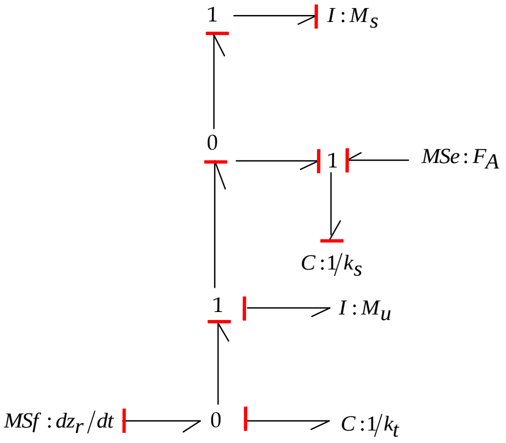


Fig. 5. BG suspension system modeling.

The input of this system is the road profile. It is modeled by a modulated source of flux MS_f. The sprung mass and unsprung mass are modeled with inertial I bond graph component. The suspension is composed by two elements associated in parallel: the first is a spring with stiffness. That is modeled by an element of the capacitive energy storage *C*. The second is the force generated by the actuator. It is modeled by a modulated source of effort MS_e. The wheel is represented by a spring which is modeled by a capacitive element for storing energy *C*.

5.3 Application of BG Tool for Linear Actuator Modeling

The mathematical model of the actuator leads to the bond graph model shown in Fig. 7. From the equations (3), (4) and (6), K_d and K_q are substituted and represent the constants of the actuator EMF. They are decrived by expressions (7) and (8).

$$K_d = N_p L_q i_q \qquad (7)$$

$$K_q = N_p \left(L_d i_d + \sqrt{\frac{3}{2}} \hat{\phi}_f \right) \qquad (8)$$

The simulation model of the linear actuator is established under the 20- SIM environment.

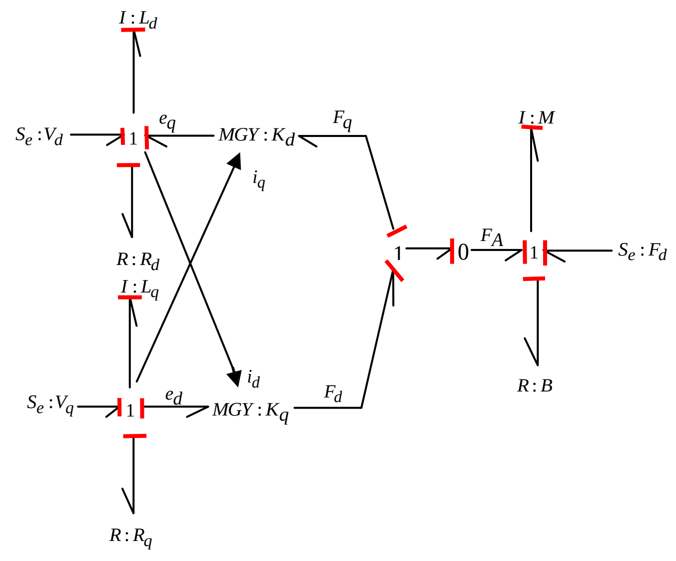


Fig. 6. BG TPMLSA modeling.

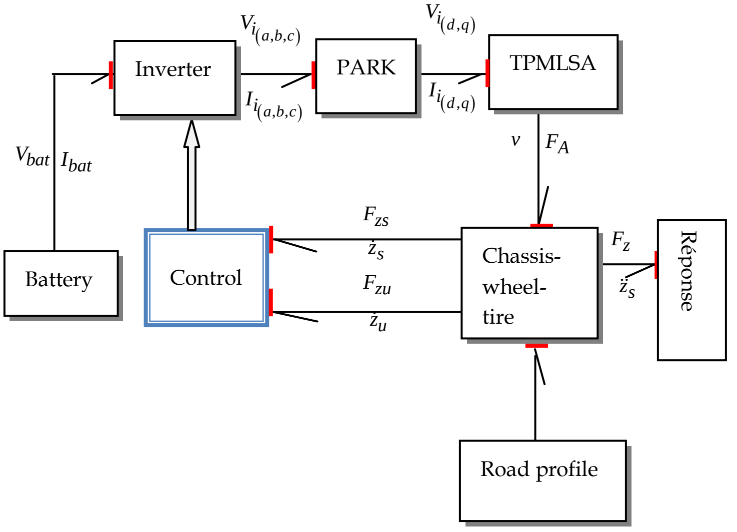


Fig. 7. Word BG model of the active suspension system.

The BG model of the TPMLSA is given in Fig. 6. This actuator is composed by two parts: electrical and mechanical dynamics. Electrical part is composed by: input voltage source (V_d and V_q), electrical resistance (R_d and R_q), inductance (L_d and L_q). These elements are modulated respectively by: source of effort, resistive element R, and inertia element I.

The mechanical part of the actuator is composed of mass M, viscous friction parameter B. These elements are modulated respectively by inertia I element and by resistive element R. These two parts are connected to a modulator gyrator, which ensures the electrical-to-mechanical transformation and conversely.

6 SIMULAITON RESULTS

The word BG represents the technological level of the model where the global active suspension system is composed of six subsystems (Fig.7): battery, inverter, PARK transformation, TPMLSA model, chassis-wheel-tire and road profile. The used variables are defined by power variables and are represented by the effort-flow.

This system is built and simulated with the BG model using 20-SIM software. This software is used to model, analyze and control the mechanical systems [16].

In this simulation, the disturbance z_r is introduced on the road state. It is presented in Fig. 8 and described by equation (9):

$$z_r = \begin{cases} a\,(1-\cos\omega t) & \text{if } 1.25 \le t \le 1.5 \\ -a\,(1-\cos\omega t) & \text{if } 4.25 \le t \le 4.5 \\ 0 & \text{else} \end{cases} \qquad (9)$$

With a : the amplitude of the disturbance on the road.

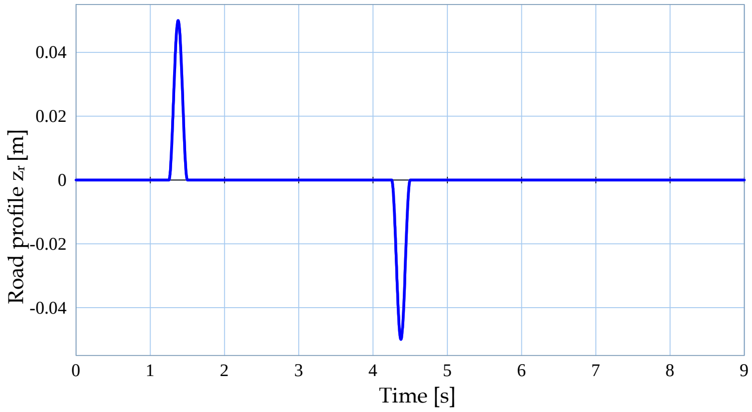


Fig. 8. Road profile.

The specifications and parameters of the active suspension system are shown in Table II.

TABLE 2
SPECIFICATIONS AND PARAMETERS OF THE ACTIVE SUSPENSION SYSTEM.

	Specifications	Notation	Value	Units
TPMLSA	Statoric inductance	L_S	0.825	mH
	Statoric resistance	R_S	54.4	$m\Omega$
	Linkage flux	ψ_f	104.5	mWb

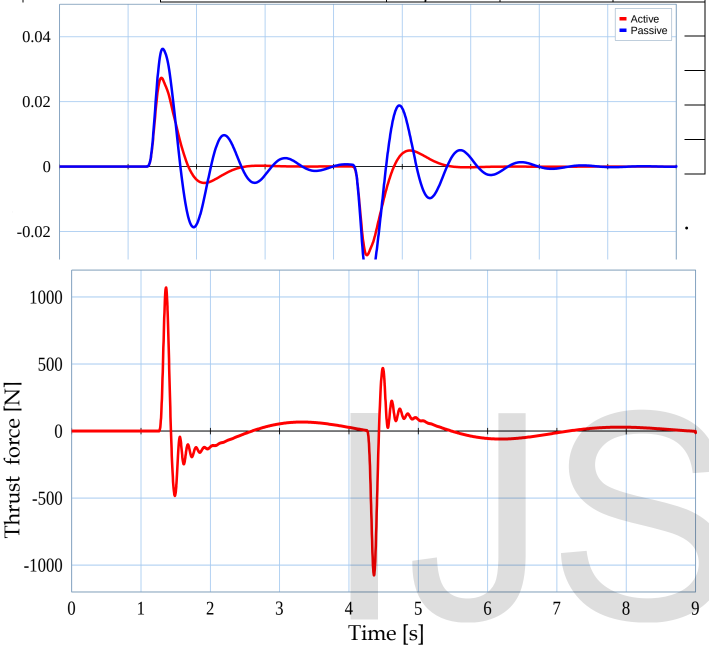


Fig. 9. Variation of the actuator force.

Fig. 10 and 11 show respectively the car body displacement and acceleration of active and passive suspension systems. The suspension deflection for both active and passive systems is shown in Fig.12.

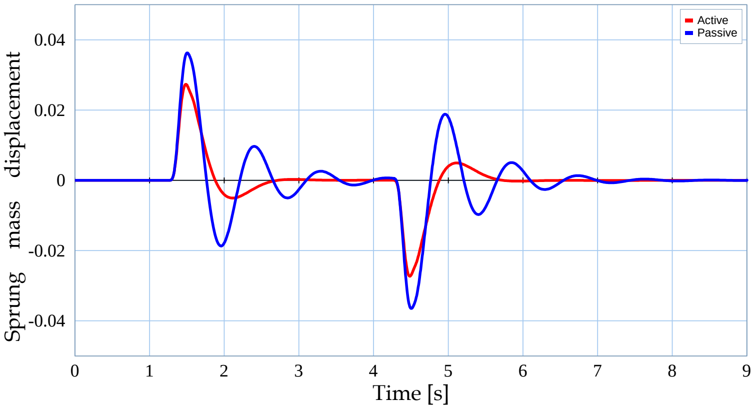


Fig. 10. Sprung mass displacement of active and passive suspension systems.

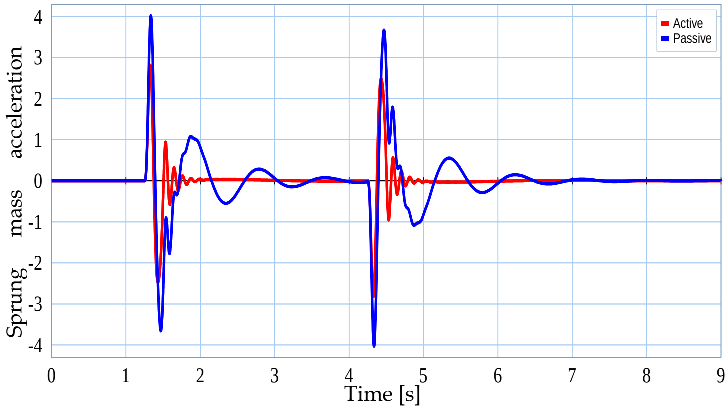


Fig. 10. Sprung mass acceleration of active and passive suspension systems.

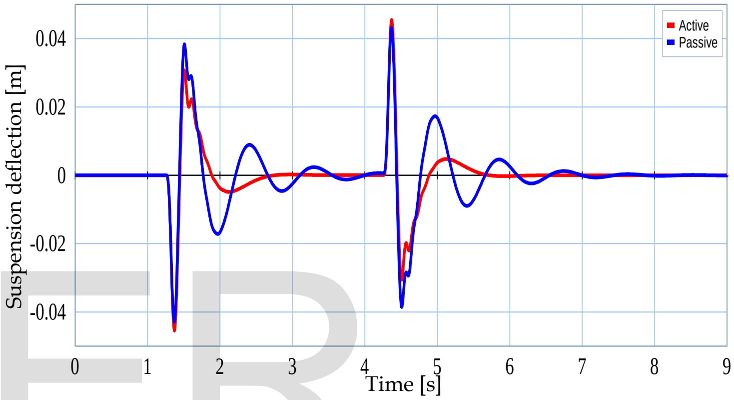


Fig. 12. Suspension deflection of active and passive suspension systems.

The simulation results show that the overshoot peak value and stabilization time are improved for the active system compared to the passive system, as shown respectively by Tables III and Tables IV for the first positive peak of the road state, Fig.9.

TABLE 3
THE COMPARATIVE REDUCTION OF PEAK VALUE OF TWO TYPES OF SUSPENSIONS.

	Case of passive suspension	*Case of active suspension*	*Reduction of peak value*
Sprung Mass Acceleratio $\ddot{z}_s$	4 m/s²	2.8 m/s²	30 %
Sprung Mass displacemen z_s	0.036 m	0.026 m	27.7%
Suspension deflection $z_s - z_u$	0.039 m	0.030m	23.08 %

TABLE 4
THE COMPARATIVE STABILIZING TIME OF TWO TYPES OF SUSPENSIONS.

	STABILIZING TIME	
	Case of passive suspension	*Case of active suspension*
Sprung Mass Acceleratio $\ddot{z}_s$	4	2.4
Sprung Mass displacemen z_s	4	2.6
Suspension deflection $z_s - z_u$	4	2.6

Comparing the simulation results developed in this paper, we can conclude that the active suspension system is more preferment and robust than the passive one.

Using the BG tool can be considered as an efficient modeling tool especially for heterogeneous dynamical system. Added to, using BG let's to obtain a systematic development of the numerical models and also, to design modular templates easly.

7 CONCLUSION

This paper presents the modeling of the automotive suspension system by the energetic approach: Bond Graph. This system is simulated by the software 20-SIM. Firstly the automotive suspension system (passive and active) is modeled. Secondly, modeling of the vertical dynamic behavior of the quarter active suspension model was built by the bond graph. Thirdly, these simulations present a comparison between active and passive suspension systems and the advantage of the first one.
The simulation results of this model obtained using the Bond Graph technique is similar to those obtained by other complicated and expensive software, reserved for complex systems.

From these results, we conclude that the bond graph approach is powerful methodology for solving, modeling and analysis complex engineering problems. Through it is simple, does not take account of mathematical equations and its structural properties.

Nomenclature

The meaning of all the parameters used in the modeling of the active suspension is presented in Table V.

TABLE 5
PARAMETERS NOMENCTATURE.

Suspension parameters	
Symbol	**Description**
k_t	spring coefficients of the tire
k_s	spring coefficients of the suspension
m_s	sprung mass
m_u	unsprung mass
z_r	road displacement
z_s	sprung mass displacement
z_u	unsprung mass displacement
$\dot{z}_s$	sprung mass velocity
$\dot{z}_u$	unsprung mass velocity
$\ddot{z}_s$	sprung mass acceleration
$\ddot{z}_u$	sprung mass acceleration
F_{zs}	Vertical suspenssion force
F_{zu}	Vertical tire force
Actuator parameters	
Symbol	**Description**
$V_d - V_q$	d and q voltage
$i_d - i_q$	d and q current
$\psi_d - \psi_q$	d and q flux
ψf	flux of permanent magnetic
$L_d - L_q$	d and q statoric inductance
$R_d - R_q$	d and q statoric resistance
F_d	load force
F_A	actuator force
F_f	friction force
B	friction force coefficient
v	linear speed
N_p	electrical position constant of the TPMLSA
τ_p	pole pitch
M	TPMLSA mass

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