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**In Mechanics and Systems Engineering**

## TOPIC

## Study of active vehicle suspension systems with fuzzy logic controller

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I thank **god** for giving us life , health , courage and the will to undertake this journey and appreciate the fruit the effort

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Finally I extend my sincere thanks to my family and all my friends for their support over many years of study

# Dedication

I dedicate this work to my dear parents, and all my family with their
never-ending support, assistance and

encouragement

I also dedicate my friends, my colleagues of Mechanical and
engineering of systems who gave me support when

I needed

# Abstract

The objective of this work to study the active and the passive suspension for compared it with the sky-hook model reference , with different road profile .The performance of the controller is compared with fuzzy logic controller and the active suspension system by performing computer simulations through the MATLAB and SIMULINK

**KEYWORDS:** the active, the passive, the sky-hook, fuzzy logic controller, road profile.

# Résumé

l'objectif de ce travail est d'étudier la suspension active et passive pour la comparer avec la référence du modèle de crochet du ciel, avec un profil de route différent. La performance du contrôleur est comparée au contrôleur de logique floue et au système de suspension actif en effectuant des simulations par ordinateur à travers le MATLAB et SIMULINK

**MOTS-CLÉS** : le actif, le passif, le ciel-crochet, contrôleur de logique floue, profil de route.

# ملخص

الهدف من هذا العمل هو دراسة التعليق النشط والسالب لمقارنته بمرجع نموذج هوك السماوي مع صورة مختلفة للطريق، لمقارنة أداء وحدة التحكم مع جهاز تحكم منطقي غامض ونظام التعليق النشط عن طريق إجراء المحاكاة الحاسوبية من خلال ماتلاب و سيمولينك.

الكلمة الرئيسية : النشطة، السلبية، سكاي هوك، تحكم منطق غامض، لمحة الطريق.

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# General introduction

A car suspension system is the mechanism that physically separates the car body from the wheels of the car. The purpose of suspension system is to improve the ride comfort, road handling and stability of vehicles. Apple yard and Well stead have proposed several performance characteristics to be considered in order to achieve a good suspension system. Suspension consists of the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. In other meaning, suspension system is a mechanism that physically separates the car body from the car wheel. The main function of vehicle suspension system is to minimize the vertical acceleration transmitted to the passenger which directly provides road comfort [25].

An active suspension system has the ability to store, dissipate and to introduce energy to the system. It may vary its parameters depending upon operating conditions. Generally, traditional suspension consists springs and dampers are referred to as passive suspension, then if the suspension is externally controlled it is known as a semi active or active suspension [25]. In other way, active suspension can gave better performance of suspension by having force actuator, which is a closed loop control system, fuzzy logic have been used in the area of active suspensions systems .

In this study, a mathematical model for the passive and active suspensions systems for quarter car model that subject to excitation from a road profile using fuzzy logic controller is conducted. Will be compared the active and the passive suspension of a degree freedom of the quarter vehicle compared to the sky-hook reference model with different road profile. The performance of the controller is compared with fuzzy logic controller and the active suspension system by performing computer simulations through the MATLAB and SIMULINK toolbox.

# Chapter I:

The suspension

## I.1  Introduction

Each moving traffic  is  exposed to vibrations due to  the deformations which the profile of the  road  presents.  These vibrations to which the bodies of  the vehicle are  subjected,  are transmitted  mainly  to the passengers, from  where the need to  decrease them to  reduce the harmful effects of them and to  make them to  lerable. Thus, the man  very quickly became aware of the need for returning the profile of the uniform roadway.

In  spite  of the evolution of the research  results to  improve flatness of the coating of the roads,  the  lack of comfort persists.  It is all  the  more true as  the users are  sometimes compelled to roll on   ways hardly suitable  for  motor  vehicles, to  even  make except track, where as the  vehicles  do  nothing  but more  and  more quickly run. Thus the  research  efforts were  as  directed  towards  the  improvement of the suspension of the vehicles, in   order to improve as   well comfort of it as   the   security. The search more   and   more of comfort and security gave a new dimension and  a more important weight to this concern .

With  its  beginnings,  the passive suspension  ( without contribution  of external  energy ) , consisted  of  bodies deformable and elastic (roll or leaf  springs, blocks of rubber, mattress of fluids, etc)  nowadays,  it understands  also shock  absorbers. The active suspension  was  born with the   external contribution of energy.

In fact, the study of a suspension is complex because it brings into play [1]

- ➢ Suspended bodies (driving, gear box, radiator, etc)
- ➢ Not suspended bodies (travelling train, consisted the axles, wheels and the bridg
- ➢ Bodies of connection  between the two first and of which  the suspension is part

In our approach of   optimization of the parameters   of    the system of regulation of an active suspension by the genetic algorithms, we will treat following factors:

1. Handling of the vehicle: to ensure an adherence of the wheel on the profile of the road, some is the deformations (for better traction and braking)
2. The stability of the vehicle: to  try to  stabilize  the vehicle some is the operations (turn, braking …), and to decrease pitching and rolling

3.  Vibratory  insulation  (comfort): to  initially  isolate  the vibrations transmitted  to the bodies   from the vehicle and the passengers in the second place
4.  The allowed race: to ensure  a  protection of  the elements or  bodies of  the vehicle  by  fixing   the dynamic deflection of  the suspension

For that it is necessary:
- To ensure a force of contact constant wheel-road
- To decrease vertical and longitudinal accelerations of the frame, while basing itself on well   defined standards

## I. 2  The role of suspension

The suspension of  the  cars  is  the system which  initially supports  the  weight  statics of the vehicle. Moreover, this system must reduce or eliminate the vibrations generated by forces of  the wind,   forces of  braking and   irregularities of  the roadway.
To control the vibration, the analysis of the following parameters is very important:

1.  The acceleration of the body of the vehicle
2.  The deflection of the suspension
3.  The deflection of the wheels

At  the  time  of  the  systems design of  suspension, the objective  of  this  last  is to minimize  the acceleration of   the body of  the vehicle,  the  deflection of the suspension and the  deflection of the wheel.  It  is  shown  that with a weak  acceleration of the body  of the vehicle,  one  has more comfort  and  that minimal deflections  of  the suspension  and  wheel increase   the contact between  the wheel and the roadway what is translated by more security and of stability.

## I.3  Types of suspension System

In general, there are three types of the suspension system [13]
1.  Passive suspension
2.  Semi-active suspension
3.  Active suspension

### I.3.1  Passive Suspension

The conventional suspension system is passive suspension system. It has two elements one of them is damper and another is spring. In this passive suspension, the purpose of the dampers is to dissipate the energy and the spring is to store the energy.

The springs are frequently used to store kinetic energy from moving components during deceleration and release this energy during acceleration to reduce peak loads. If a load exerted to the spring, it will compress until the force produced by the compression is equal to the load force.

For this type of suspension system damping coefficient and spring stiffness are fixed characteristics therefore this is the main weakness as parameters for ride comfort and good handling vary with different road surfaces, vehicle speed and disturbances.

### I.3.2  Semi-active Suspension

The component in the semi-active suspension system is similar with passive suspension system and where external energy is needed in the system, it uses the same function of the active suspension system. The differentiation with passive suspension system is that the damping coefficient can be controlled .The fully active suspension is modified thus the actuator is only capable of dissipating power rather than supplying it as well. The actuator then becomes a continuously variable damper which is theoretically capable of tracking force demand signal independently of instantaneous velocity across it.

### I.3.3  Active suspension

The active suspension system consists an additional element in the conventional suspension, which the main component of it is an actuator that is controlled by a high frequency response servo valve and which involves a force feedback loop.

In general, the duty of sensor in active suspension systems is to measure suspension variables such as body velocity, suspension displacement, and wheel velocity and wheel or body acceleration. In an active suspension system, actuators that supply additional forces improve the passive elements. A feedback control law via data from sensors attached to the vehicle determines these additional forces.

## 1.4  Description of the model of   quarter  of vehicle

The traditional suspensions which equipped the vehicles used springs assembled in parallel with passive shock    absorbers    the figure1.1 watch a system of suspension with    degrees of freedom. It represents one of the four  corners of the vehicle, and is  named  commonly model of a quarter of vehicle [12].

This system is composed of  the suspended mass (m), the  not  suspended  mass (wheel), it damping   coefficient  (b)   of the passive shock  absorber,   the coefficient of stiffness of   the spring linear (k).
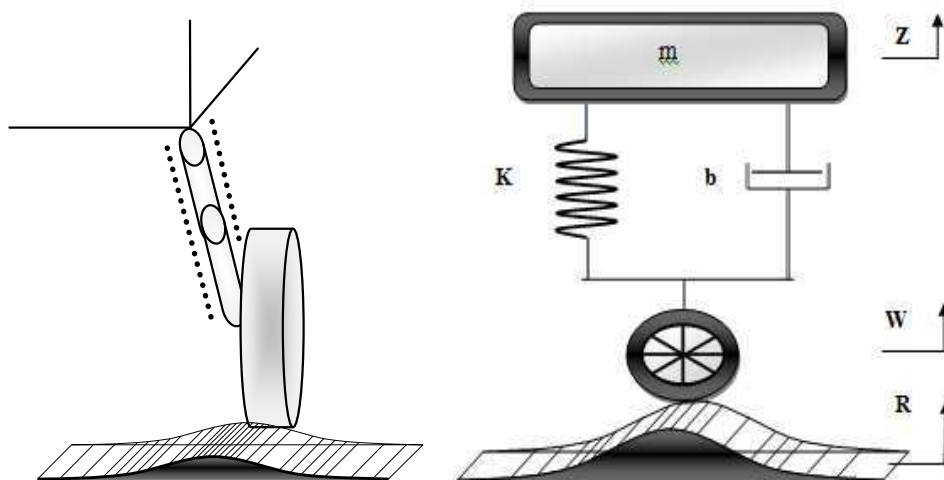
**The figure I.1** The quarter vehicle model

## I.5   Passive suspension to a degree of freedom

The passive suspension is of almost linear nature, it is based on the principle of dissipation of the energy stored by the spring and the shock absorber, the generated force, modeled by the model of Kelvin is a linear function of displacement and speed relative of the suspension. Although this model is used by the majority of the industrialists, it has limitations when it is a question of improving the comfort and the stability of the road vehicles, these limitations have pushed the researchers to find other models of suspensions [14].

## I.5.1 Model of a passive suspension

It is a suspension carried   out using passive  elements such  as springs,   shock  absorbers, whose  manufacturing is simple and  raised the  enough performances, but which remains  very limited compared  to the ambitions of the  manufacturers and the needs  for the user (comfort, security).

The  model  of  a  passive  suspension  of  a  quarter  of  a  vehicle  to  a  degree  of  freedom  (the figure.I.2)  [2-3-4].
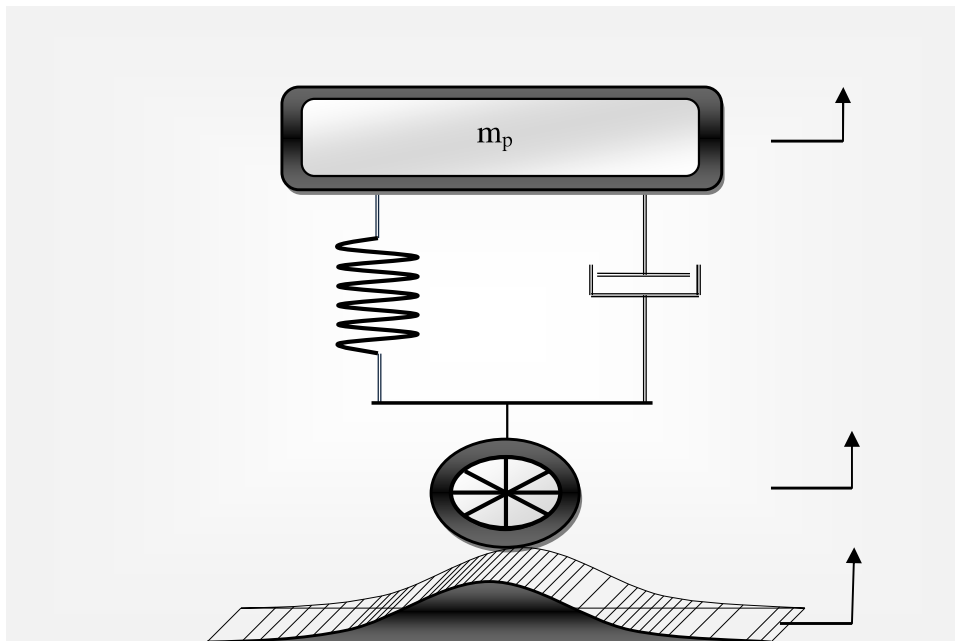


**Figure I.2**  Model of passive suspension

Where:

$m_p$ [kg]        = mass of the frame of a quarter of vehicle

$b_p$  [N/m]      = coefficient of stiffness of the spring

$K_p$ [N/m/ s]    = damping coefficient

## I.5.2 Dynamic equation

The vibratory behavior is governed by the differential equation

$$m_p \ddot{z}_p = -k_p(z_p - w) - b_p(\dot{z}_p - \dot{w})$$

( I .1)

| | |
|---|---|
| $z_{p(m)}$ | = vertical displacement of the mass. |
| $x_p = z_p - w$ | = relative displacement enters the mass and the wheel. |
| $k_p(z_p - w)$ | = force developed by the spring. |
| $b_p(\dot{z}_p - \dot{w})$ | = force developed by the shock absorber. |

## I.6   Strategies of control

### I.6  Control skyhook

One of the most  popular controllers and most  used for the active suspension in application commercial is  the   concept  of control skyhook. In  the strategies of control skyhook a shock absorber  is   placed between the suspended mass and apoint imaginaries in the sky.
It is equivalent to the   application of a force proportional and opposite   within   the   meaning of speed of the mass suspended  $\dot{z}_m$ with an amplification so that it has no force applied  to the  not suspended mass .

Such an arrangement proves very effective byordering the acceleration of the suspended mass $\ddot{z}_m$  and is attractive because of the inherent simplicity from a practical point of view.

Unfortunately,  this approach sky-hook is  not  practically plan table  because it is  not possible find it a fictitious point to   fix the shock   absorber at  the sky-hook.
In   practice, we call on the use of an actuator    between masses suspended and not suspended even the figure I.3.

However, this leads to the deterioration  of   the  dynamic   performance   of the not suspended mass    since the entry of the   control force  is  applied   as  well to the suspended mass   as not suspended.  Thus, the dynamic  response of the   system  of  suspended practical sky-hook is considerably worse than that of the system of suspension based by sky-hook ideal.

## I.6.2 Model of a suspension (Sky-Hook)

The model of the Sky-Hook suspension represented by the figure I.3 is regarded as a reference for the systems design of systems of suspensions [2-3-4].
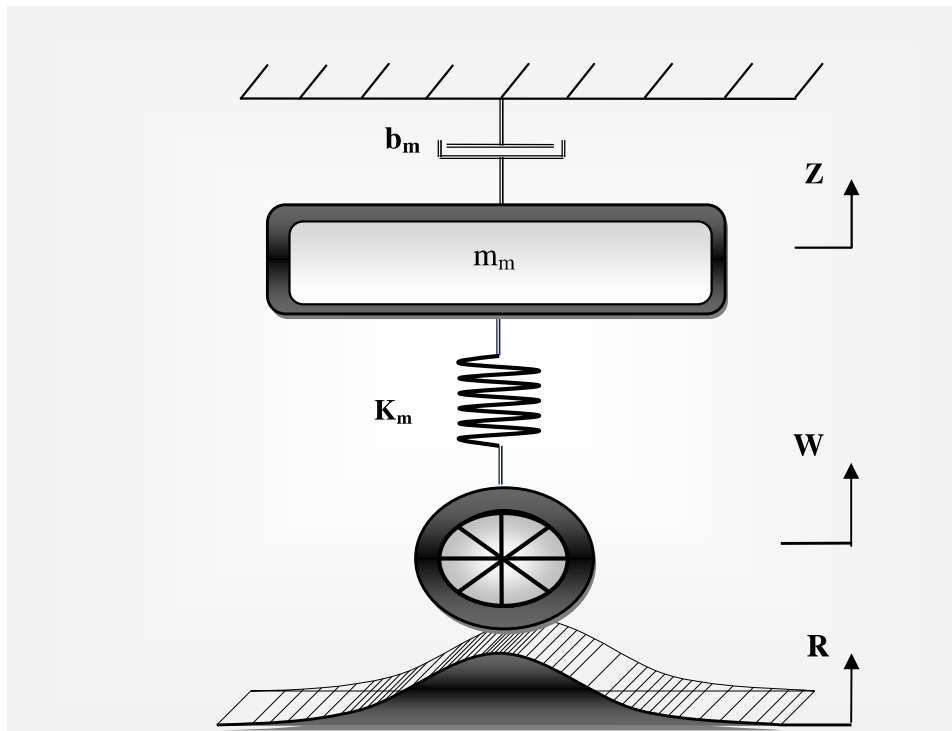


**Figure. I.3** Model of a sky-hook suspension

Where

$m_m$ [kg]          = suspension mass of quarter car.

$k_m$ [N/m]         = the coefficient of stiffness of the spring.

$b_m$ [N/m/ s]     = the coefficient of the depreciation of the sky-hook model .

## I.6.3 Dynamic equation

The vibration behavior is governed by the differential equation

$$m_m \ddot{z}_m = -k_m(z_m - w) - b_m \dot{z}_m$$

( I .2)

It notes that the applied force *F* is of the form

$$F = -k_m(z_m - w) - b_m . \dot{z}_m$$

( I .3)

We designate by the deflection the relative displacement between the earth and the wheel and one writes

$$x_m = z_m - w$$

( I .4)

## I.7  The active suspension to a degree of freedom

One of the problems  encountered in these types of  suspension is the formulation   of the force produced.

Certain researchers worked on the determination   of a mathematical   model which   represent the force generated by these systems. We know that the active suspension generates one force which controls the mechanical system    continuously.

The  purpose  of the use of this  kind  of suspension  is to  reduce the transmission   risks of vibrations and to increase the factor of stability [14].

## I.7.1 Model of the active suspension

In order to improve the performance of passive suspensions, one introduced a generator of effort (active element) placed in parallel with the spring and shock absorber as shown in the figure I. 4  [2-3-4-5].
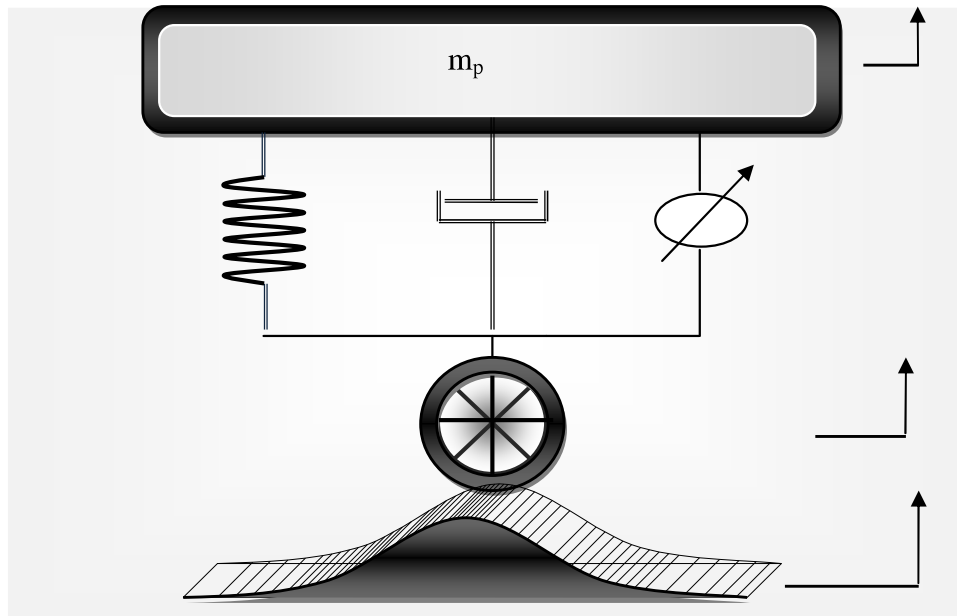
**Figure I.4** Model of the active suspension

The model is characterized by

$m_p$  [kg]          =suspension mass of a quarter.

$k_p$  [N/m]      = coefficient of stiffness of the spring.

$b_p$   [N/m/ s]  = coefficient of depreciation of a spring liabilities.

$u$  [N]           = force applied to the suspension governed by the actuator dynamic.

## I.7.2 Dynamic equation

The dynamic equation which describes the movement of the system is

$$m_p \ddot{z}_p = -k_p\left(z_p - w\right) - b_p\left(\dot{z}_p - \dot{w}\right) + u \qquad\qquad (\text{ I }.5)$$

With

$z_p$  = vertical movement of the earth.

$x_p = z_p - w$  = deflection and relative displacement between the earth and the wheel.

## I.8   Degrees of freedom of a vehicle

A vehicle can be  driven according  to the six  degrees of freedom, three translations and three rotation [12]

1. The advance of the vehicle : according to X.
2. The shifting of the vehicle : according to Y.
3. The pumping of the vehicle: according to Z.
4. The rolling of the vehicle: ($\theta$). Around X.
5. The pitching of the vehicle: ($\varphi$). Around Y.
6. The bouncing  of the vehicle: ($\psi$). Around Z.

In our study one considers only the pumping of the vehicle
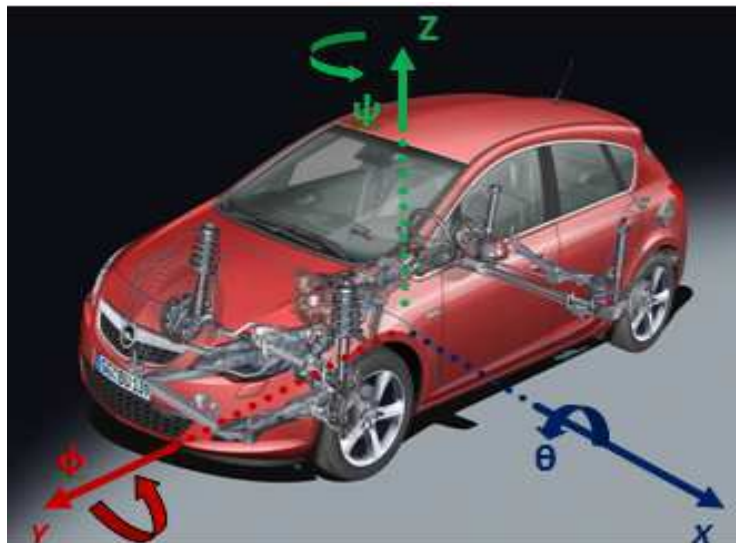


**Figure I.5** Degrees of freedom of a vehicle

## I.9 Vehicle Suspension Models

### I.9.1 The quarter vehicle model

The quarter-car model suspension will represent the sprung mass, while wheel and axles are illustrated by the unsprung mass . The spring, shock absorber and a variable force-generating element placed between the sprung and unsprung mass constitutes suspension, the system as shown in Figure I.6.
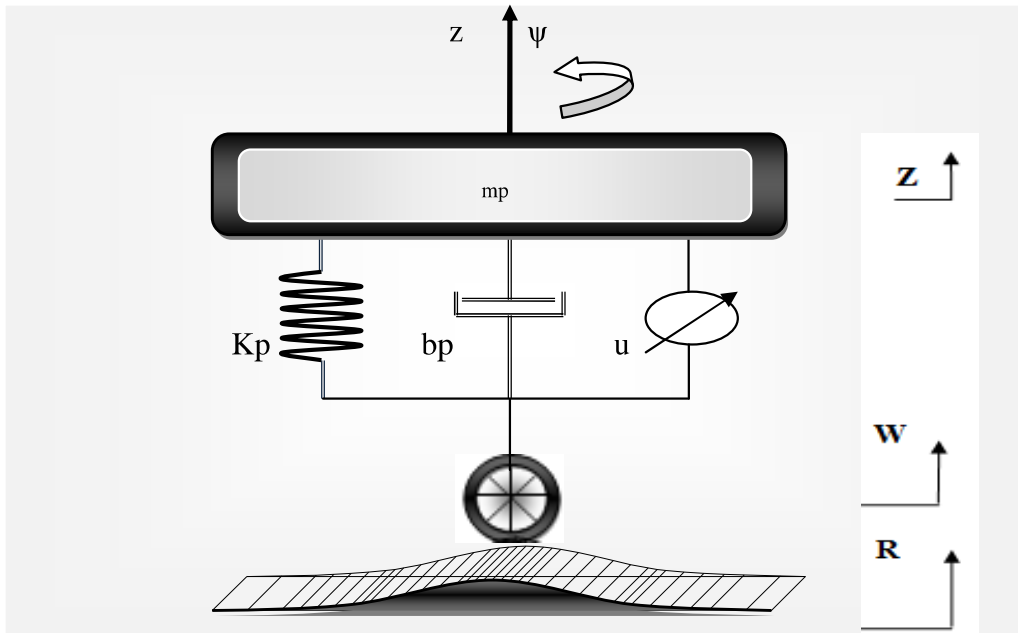
**Figure I.6** The quarter vehicle model to tow degrees of freedom

### I.9.2  The half vehicle model

Multi-body dynamics has been used extensively by automotive industry to model and design vehicle suspension. A simplified half model with four degrees of freedom are the pumping of not suspended masses (wheels) and of the suspended mass (mp) and rolling of the vehicle  , the system as shown in Figure I.7.
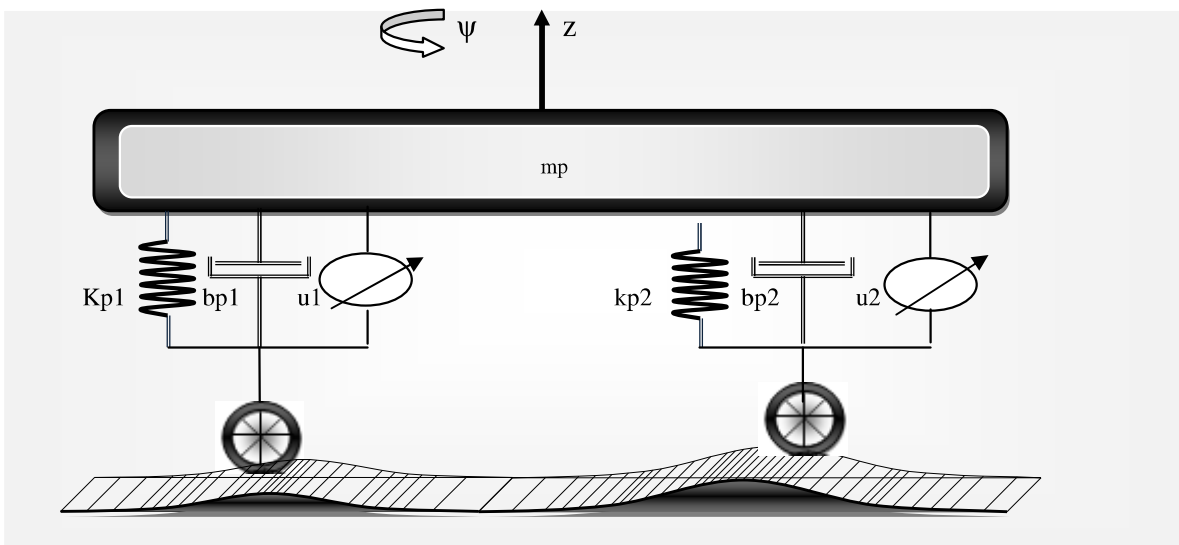


**Figure I.7** The half vehicle model to four degrees of freedom

### I.9.3 The full vehicle model

The physical model of the investigated system was formed by a full vehicle model and a human model by considering the human body as a dynamic system as well.

The human model was incorporated into a non-linear full vehicle model the body and wheel masses of the vehicle were assumed to be rigid bodies.
Compared to the other systems defined previously, the complete model of vehicle takes into account all the movement possible, the three displacement (advance ,shifting and pumping) and of the three rotation (rolling, pitching and bouncing) for each element .

The full vehicle model to seven degrees of freedom is shown in Figure I.8. The model considered for simulation consists of seven degrees of freedom (DOF), which include longitudinal and lateral motions and yaw motion of the vehicle as well as the rotational dynamics of the four wheels .
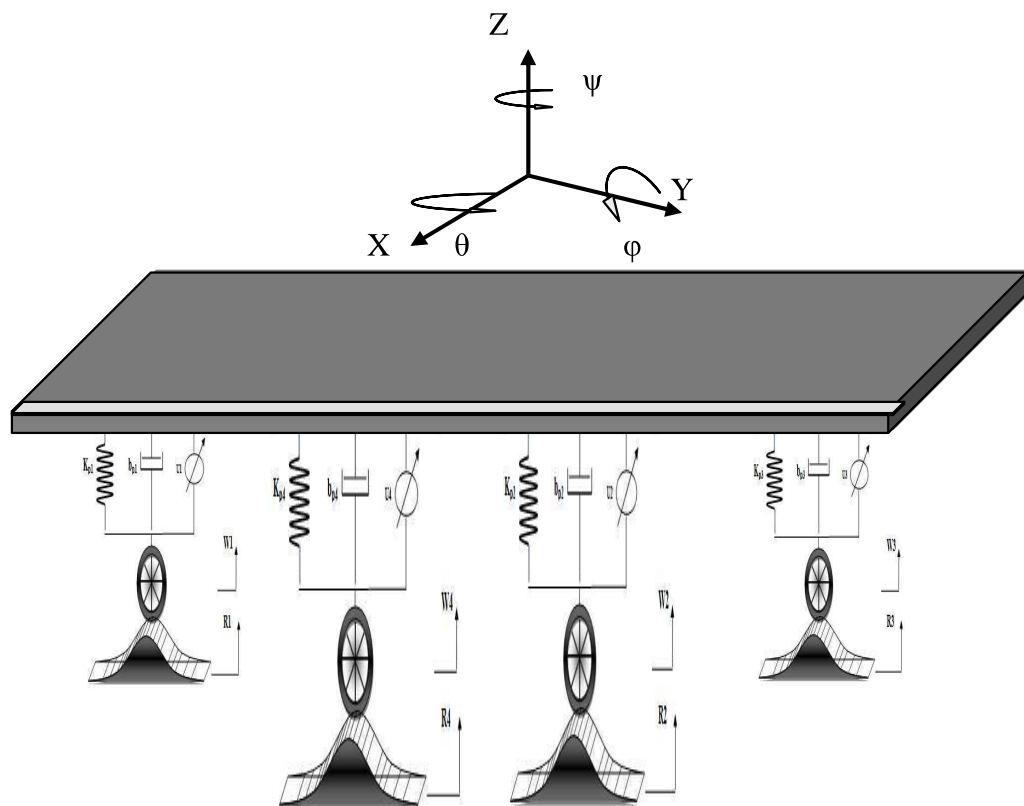


**Figure I.8  The** full vehicle model to seven degrees of freedom

## I.10  Linear active suspension system

   Active suspension system has the ability to response to the vertical changes in the road input.  The damper or spring is interceding by the force actuator., This force actuator has it own  task which is to add or dissipate energy from the system. Therefore active suspension system offer better riding comfort and vehicle handling to the passengers[10].

   The force **u** developed by the actuator is determined from a control strategy aimed to optimize the dynamic behavior of the system. Among these strategies the theory of optimal controls linear (LQR) [7]. The Figure I.9. shows simple block diagram to explain how the active suspension can achieve better performance.

input                                                                    output
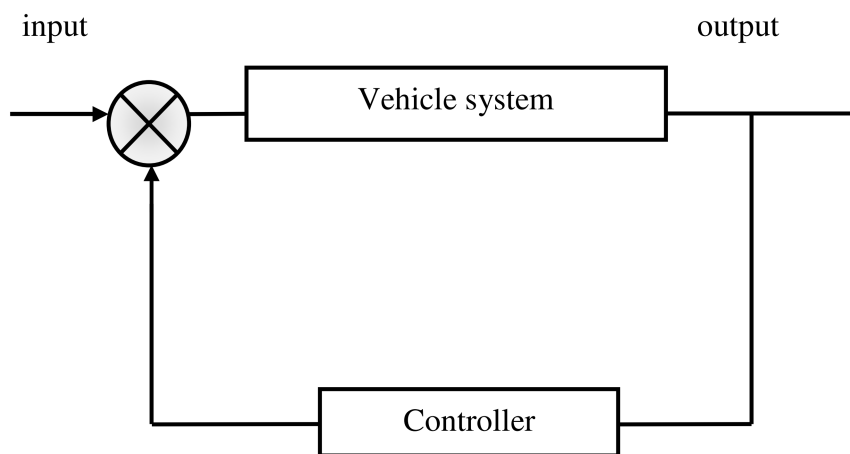


**Figure I.9** Active suspension of control system

## I.11 The method of the optimal control LQR linear

This theory allows to obtain, under some constraints the optimum of controller, to the extent where the vector of state, the vector of controller and the vector of disturbance, are linked by a relationship of type:

$$\dot{X} \;=\; A\ X + B\ U + D\ W \tag{I .6}$$

Where

$X(t)$ = vector of state

$U(t)$ = vector of command

$W(t)$ = vector of disturbance assumed to be white noise of zero mean and covariance matrix

      $K$.

*A, B* and D are matrices extracted constants of differential equations that define the system.

The aim being to minimize performance index J defined in the following:

$$J = J_1 + \rho_1 J_2 + \rho_2 J_{3+} \rho_3 J_4 \qquad\qquad\qquad ( \text{I} .7)$$

$J_1$, $J_2$, $J_3$ and $J_4$ are factors respectively related on comfort, the race of the suspension, the

 handling and to the cost of operation.

$\rho_1$, $\rho_2$ and $\rho_3$  are factor loadings.

This index of performance J can write in the form:

$$J \;=\; E\left\{ X^T . U^T . \begin{bmatrix} Q & N \\ N^T & R \end{bmatrix} . \begin{pmatrix} X \\ U \end{pmatrix} \right\} \qquad\qquad ( \text{I} .8)$$

Where

$$J=E \{ \; X^T Q X + U^T R U + 2 X^T N U^T \} \qquad\qquad\qquad ( \text{I} .9)$$

E indicates the expectation.

The matrices **Q** and R are symmetrical. **Q** is definite non negative and **R** is definite positive.

The resolution of the problem consists in   determining the command **U** which minimizes the

index of performance **J**. This command is linear, and is worth:

$$U = -K. X \qquad\qquad\qquad\qquad\qquad ( \text{I} .10)$$

Where **K** is the matrix profit of command, given by :

$$K = B^{-1} ( N^T + B^T S) \qquad\qquad\qquad\qquad ( \text{I} .11)$$

Such as, *S* matrix symmetric defined positive, solution of the equation of RICCATTI which is:

$$S . A + A^T . S - (S . B+N) R^{-1} . (B^T S + N^T ) + Q =0 \qquad\qquad ( \text{I} .12)$$

The Figure I.10 shows simple block diagram of **LQR** control schematic
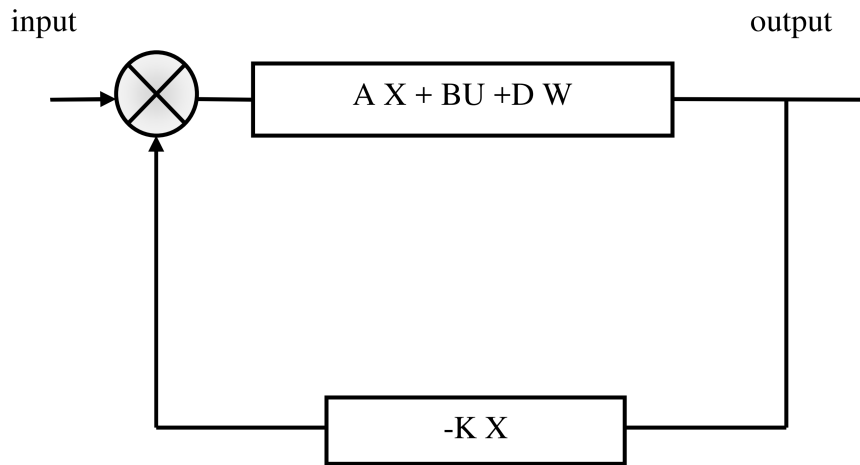


**Figure I.10**   Block diagram of LQR control schematic

## I.12 Functions of inputs

To see the various answers of our system, one excites it by the three functions of excitation, sinusoidal, impulse and echelon [12]

### I.12.1 Excitation sinusoidal

The function of sinusoidal excitation is given by

$$W(t) = w_0 \sin(\omega_n t) \qquad\qquad (I.13)$$

With

$w_0$ = maximum amplitude of excitation.

$\omega_n$ = pulsation of the system in rad/s.

### I.12.2 Excitation impulse

The function impulse is given by the expression

$$W(t) = w_0 \left(\frac{\exp(2)}{4}\right)(V\,\omega_n t)^2 \exp(-V\,\omega_n t) \qquad\qquad (I.14)$$

With

$V$    =  factor of severity of shock.

$\omega_n$   =   pulsation of the system in rad/s.

$w_0$   = maximum amplitude of  signal (m).

### I.12.3 Excitation echelon

The function echelon  is given by the expression

$$W(t) = w_0 [ 1 - \exp(-V \omega_n t) (1 + V \omega_n t) ] \tag{I.15}$$

$\omega_n$   =  pulsation of the system in rd/s.

$W_0$   = maximum amplitude of  iput.

$V$    = factor of severity of shock

## Conclusion

In this chapter, one has defines different the type  of  suspension  of  vehicle  passive, semi-active and active,  as well as degrees of freedom of a quarter , half  and full vehicle , on the  other  hand,   the  input  functions  sinusoidal, impulse and echelon which will  be  used as functions of excitation of the system of suspension .

The  optimization  of  the  active  suspension  by  a  control  law  of  LQR  supposes  that  the system is linear and that the disturbance is a white vibration of average zero , which is not always  the  case,  because  actually   the  profile  of  the  road  is  unspecified   and  the  dynamic behavior of the vehicle is not rigorously  linear.

The  need  to  develop  new  systems  of  suspensions  more  reliable  and  more  powerful  pushed the  researchers  to  find  new  methods  of  command  for  the  regulation  of  non-linear  systems, which will be the subject of the developments of the following chapters.

# Chapter II:

# Fuzzy control of an active suspension to a degree of freedom

## II.1 Introduction

The fuzzy logic, whose elementary theory was established in 1965 at the University of Berkeley (California) by the Pr. Lotfi A. Zadeh, is a concept based on a linguistic formulation of the human reasoning [8]. Its application on to the control was not possible that in 1974 thanks to the work of the Pr. E. H. Mamdani which designed and produced the first regulator by fuzzy logic.

Fuzzy logic methods can be utilized in many ways in controlled suspension systems. With appropriate membership functions and rule bases it considered to be insensitive to model. Fuzzy logic is a method of controlling a system where all input conditions are not well defined. The implementation of fuzzy logic allows the use of rule based control where by the controller is defined by abstract that give them a fuzzy quality. The linguistic control strategy of the fuzzy algorithm serves as a fuzzy process model, because of the linguistic statements from the rule base of the fuzzy logic controller, the control strategy resembles human thinking process application of fuzzy logic method is presented [17] .

We will consider in this chapter the model of active suspension of the **figure .I.4**. to which we will apply a fuzzy control developed starting from a regulator of the Mamdani type.

## II.2 Linguistic variable

A linguistic variable represents a state in the system to be regulated or a variable of adjustment in a fuzzy controller. Its value is defined in linguistic terms which can be words or sentences of a natural or artificial language.

Each variable linguistics is characterized by a set such as [14]:

$$\{ \, x \, , T(x) \, , u \, , G \, , M \, \} \tag{II.1}$$

with

$X$ = the name of the variable

$T(X)$ = the linguistic values which X can take

$U$    = universe of discourse associated with the basic value

$G$    = syntactic rule to generate the linguistic values of X

$M$    = semantic rule to associate a direction with each linguistic value

**For example**

The variable linguistics X ambient temperature can be defined with a set of terms

T (X) = {extremely cold, very cold, cold, hot, veryhot and extremely hot}

Who form his universe of the discourse U = [- 20°C,40°C].

The basic variable X is temperature.

The term cold represents a linguistic value.

## II.3  Membership function

Each fuzzy subset can be represented by its function of membership. If the set of reference is a finished unit, the values of membership are values discrete defined in [0, 1].

If the set of reference is infinite, one can represent these values like functions of membership continuous.

In general, there are different forms of membership functions such as singleton(a), triangular (b), trapezoidal (c), and Gaussian the shape of bell as the form (d) shows in Figure.II.1. [16]



(a)                                                    (b)

(c)                                                                    (d)
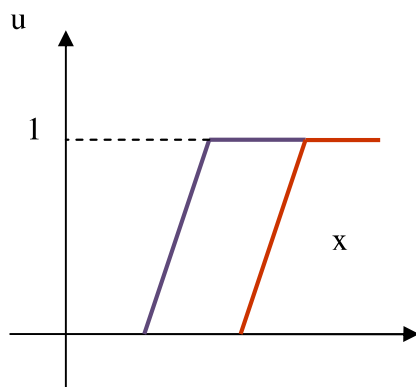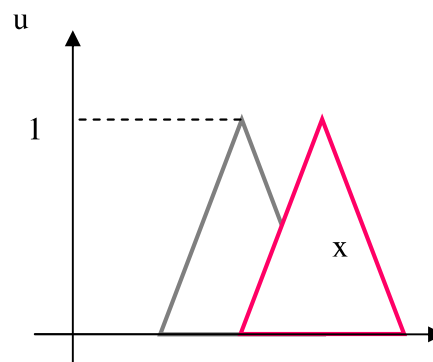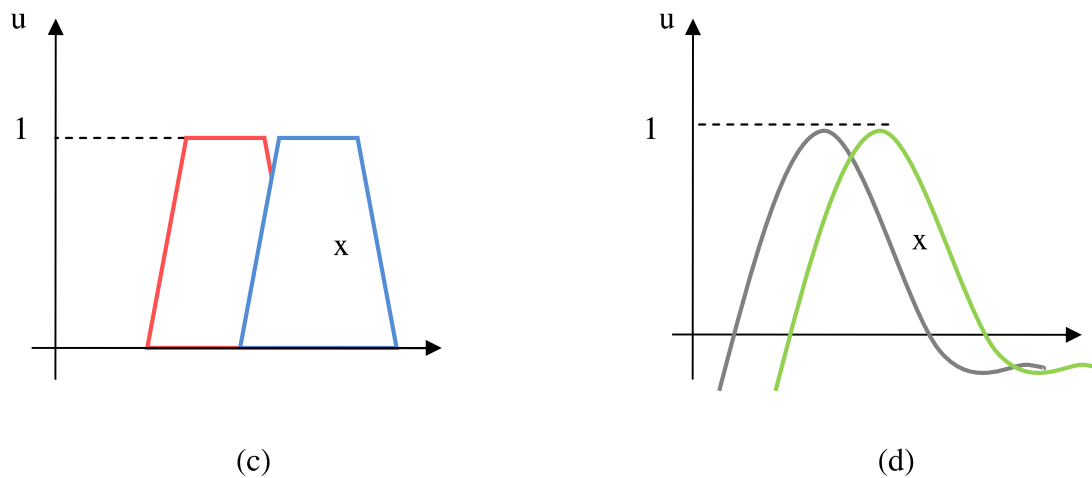
**Figure II.1** Various forms of  membership function

## II.4  Universe of the discourse

One of the   first    steps in the design of a fuzzy   application is to   define   the subset   of reference  or universe of the discourse for each linguistic variable [14].

## II.5  Linguistic rules

Principal the idea of the system   based one fuzzy   logic is to fast knowledge   human in   the forms of linguistic rules of forms **If…then**. Each rule has two shares [14]

- Previous part (condition), expressed by **IF**.
- Consequent expressed by then leaves.

ZADEH was the first to introduce the concept of fuzzy rule in the forms:
 **if**  X  is A**, then** is B there.

## II.6 The regulator of Mamdani type

Fuzzy mamdani type method turns to be an ideal approach to quicken the decision making process via converting complex equations to linguistic rules. All design factors compose input variables, and the corresponding weights and input values are produced from professional knowledge, industrial experience and product requirements.

After all input variables going through the fuzzy inference mechanism, a single recommendation score will be generated as output. According to the recommendation score of every designing scheme, developing engineers will have theoretical support to decide whether timing belt or timing chain is more preferable [15].

## II.6.1 The structure of the regulator of Mamdani type

The structure of a system regulated by fuzzy logic consists of three principal blocks: the regulator by fuzzy logic **[8]**, the control unit and the system to control figure.II.2.
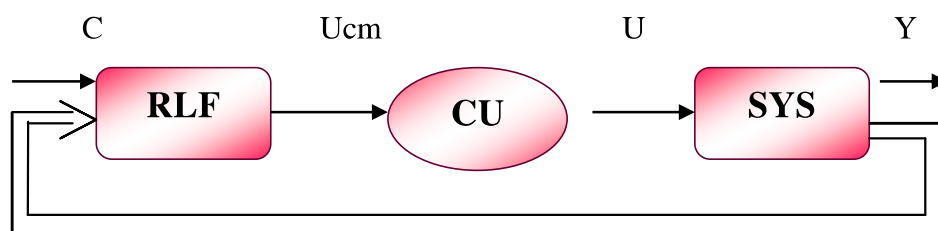


**Figure II.2**  Schematic diagram of the adjustment by fuzzy logic

## II.6.2 Structure of fuzzy logic controller

The  regulator by fuzzy logic (RLF) does  not  treat a  mathematical relation well defined, but uses inferences with several rules, being based on linguistic variables  [11] .

In figure II.3.  we will   present the general   procedure of the design of a regulator   by   fuzzy logic.   The basic configuration of a logical regulator   fuzzy   **RLF** comprises four      principal blocks

- ➢ The block of fuzzification
- ➢ The block of inference
- ➢ Knowledge bases
- ➢ The block of defuzzification

The process of fuzzy logic controller is illustrated in figure II.3
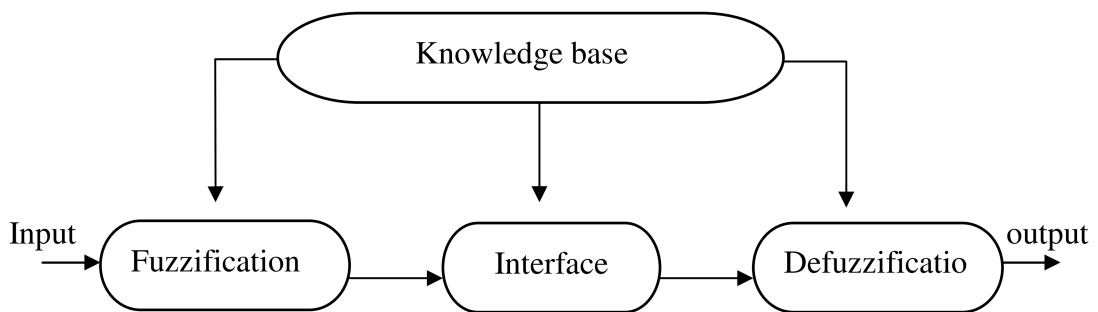


**Figure II.3**  Diagram of  fuzzy logic controller

## II.6.3 Internal structure of fuzzy logic controller

The structure of the regulator by fuzzy logic applied to our system of suspension is represented on the figure II.4
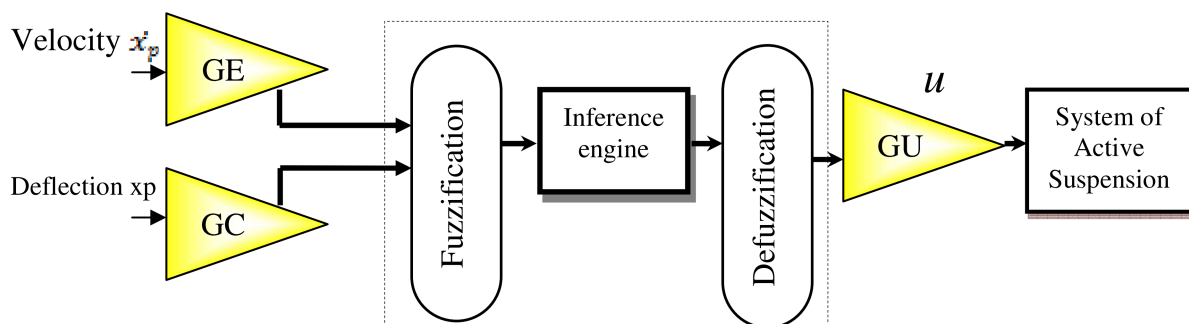


**Figure II.4** Internal structure of the regulator by fuzzy Logic

$x_p$ and $\dot{x}_p$ are the input variables of the regulator by fuzzy logic. They correspond respectively to the deflection and the velocity.

$u$ is the output. It represents the control force applied by the actuator.

**GE, GC** and **GU** are gains applied respectively to the deflection, the velocity and the control force , that values taken by these latest do not exceed the universe of the discourse **[9]**.

## II.6.4 The role of logical regulator fuzzy ( RLF)

The roles of each block can be summarized as follows [11]

➢ The **Fuzzification** block carries out the following functions

- Establishes the ranges of values for the membership function starting from the value of the input variables.

- Carry out a fuzzification function with converts the input data into suitable linguistic value .

➢ The **bloc knowledge** base is composed of the subsets of the information which we have on the process. It makes it possible to defined the membership function and the rules of the fuzzy regulator.

➢ The **bloc inference** is the heart of the regulator, which has the capacity to simulate the human decisions and deduce fuzzy control actions implication and the rules of inference.

➢ The **defuzzification** block carries out the following functions

- Establishes the ranges of values for the membership function starting from the value of the output variables signal from the deduced fuzzy signal .

- Carry out defuzzification which provides a control signal not fuzzy starting from the deduced fuzzy logic.

## II.7 Procedure of fuzzy reasoning

## II.7.1 Bloc of fuzzification

The inputs in a fuzzy regulator are in general measured using bodies of measurement who are more are of analogical type, The attribution of degrees of membership of each value of input is a passage of the physical sizes to the linguistic variables, the linguistic variables are indicated by their linguistic values .

In general, the functions of membership which represent the linguistic values are defined in triangular, trapezoidal form or in the shape of bell.
One can introduce for a variable X three, five or seven linguistic values.
On the other hand, such a choice would complicate the formalization of the rules of inference.

The standard designation of the fuzzy set is NB negative big, NM negative medium, NB negative small, ZE zero, PB positive big, PM positive medium , PS positive small. A number of linguistic values higher than seven does not bring any in general improvement of the dynamic behavior of the adjustment.

On the other hand, such a choice would complicate the formalization of the rules of inference.

## II.7.2 Bloc of inference

The inference bind the measured sizes and the variables of output by linguistic rules.

These rules are combined by using connections " **and** " and " **or** " . Let us suppose that it fuzzy system has two inputs suitably transformed into linguistic variables X, Y and an output Z, and which one defined N linguistic rules as follows [14]

**If** $x=A_1$ and $y=B_1$ **then** $z=C1$
**If** $x=A_2$ and $y=B_2$ **then** $z=C2$

In other words, in a general way, we write
**If** $x=A_n$ and $y=B_n$ **Then** $z=Cn$.

## II.7.3 Deffuzification

The result of a fuzzy inference is a membership function . It is a fuzzy subset a control unit requires a precise control signal.

The transformation of fuzzy information in to given information is defuzzification.

There are several methods of defuzzification suggested in the literature. There is no strategy .

To choose among one of these methods [14]

- method of the centre of gravity

- method of the average of the maximums

- method of TSUKAMOTO method of the weighted average

The method of the most used defuzzification, is that based on the determination of the **centre of gravity** of the function of membership resulting from all the rules of inference [**4**]

$$u(t) = \frac{\int\limits_{-x}^{+x} x_R . U_{RES}(x_R).dx_R}{\int\limits_{-x}^{+x} U_{RES}(x_R).dx_R} \qquad \text{or} \qquad u(t) = \frac{\sum \mu_i(u).dx_R}{\sum \mu_i(u)} \qquad \textbf{(II.2)}$$

**U(t)**    = membership function

**U**      = variable of output

The final control signal applied to the suspension is given by

$$U(t) = GU . u(t) \qquad\qquad\qquad\qquad\qquad\qquad \textbf{(II.3)}$$

The integral with the denominator gives surface, while the integral with the numerator corresponds at the time of surface.

$$u(t) = \frac{\sum \mu(u).dx_R}{\sum \mu(u)}$$
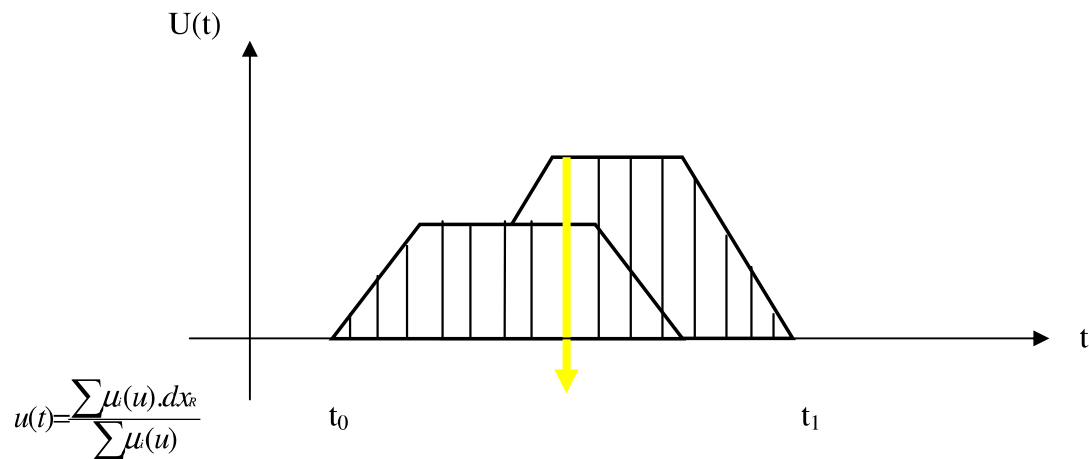
**Figure II.5** Deffuzification by the method of the centre of gravity

## II.8 Advantages and disadvantages of fuzzy logic controller :

The control of a system by fuzzy logic present has the time of the advantages and the disadvantages of which we quote mainly the following points [14]:

**Advantages**

- Not required establishment of a mathematical model of the system to be regulated
- Implementation of knowledge of the operator of the process
- Possibility of controlling systems nonlinear and difficult to model

**Disadvantages**

- Lack of precise directives for the design of a regulator
- Artisanal and non systematic approach
- Impossibility of showing the stability of the circuit of adjustment in any general information
- Precision of the adjustment relatively low
- Coherence and inference unguaranteed a priori

## II.9 The controller by fuzzy logic

### II.9.1 Fuzzification of variable (the inputs of the RLF)

Its role consists in converting the numerical values of the variables of the input in to Linguistic variables (fuzzy).

The two **inputs** as well as the **output** are fuzzified values in 7 linguistic variables are

- **NB**    : negative big
- **NM**    :  negative medium
- **NS**    :  negative small
- **ZE**    :  zero
- **PB**    :  positive big
- **PM**    :  positive medium
- **PS**    :  positive small

The generalized bell membership function is specified by thereee parameters has three functions name **gbellmf** [16].

The fuzzification  is gives thanks to the membership functions of Gaussian shape generated by the formulated [9]:

(II.3)

$$u_{li}(x, a_i, b_i, c_i) = \frac{1}{1 + \left[\left[\frac{x - c_i}{a_i}\right]^2\right]^{b_i}}$$

With

$a_i$  =  length of the field of the bell

$b_i$  =  Declines in both sides of the bell

$c_i$  =  Position of the top of the bell

The set {$a_i$ $b_i$ $c_i$} constitutes the parameters of the adjustment associated with the various linguistic variables of the controller by fuzzy logic.

The settings chosen for the membership functions are **[9]**

The functions bells associated with .Table II.1.a, .II.1.b and .II.1.c respectively are illustrated by the figures .II.6.a , .II.6.b and .II.6.c

### II.9.1 .1 The deflection   $x_p$

**Table. II.1.a**

| | $\{a_i, b_i, c_i\}$ |
|---|---|
| **NB** | $\{5.0, 1.5, -6.0\}$ |
| **NM** | $\{2.0, 1.5, -3.0\}$ |
| **MS** | $\{2.0, 1.5, -1.0\}$ |
| **ZE** | $\{2.0, 1.5, 0.0\}$ |
| **PS** | $\{2.0, 1.5, 1.0\}$ |
| **PM** | $\{2.0, 1.5, 3.0\}$ |
| **PB** | $\{5.0, 1.5, 6.0\}$ |

**Table II.1.a** The parameters of  the membership function of the deflection x
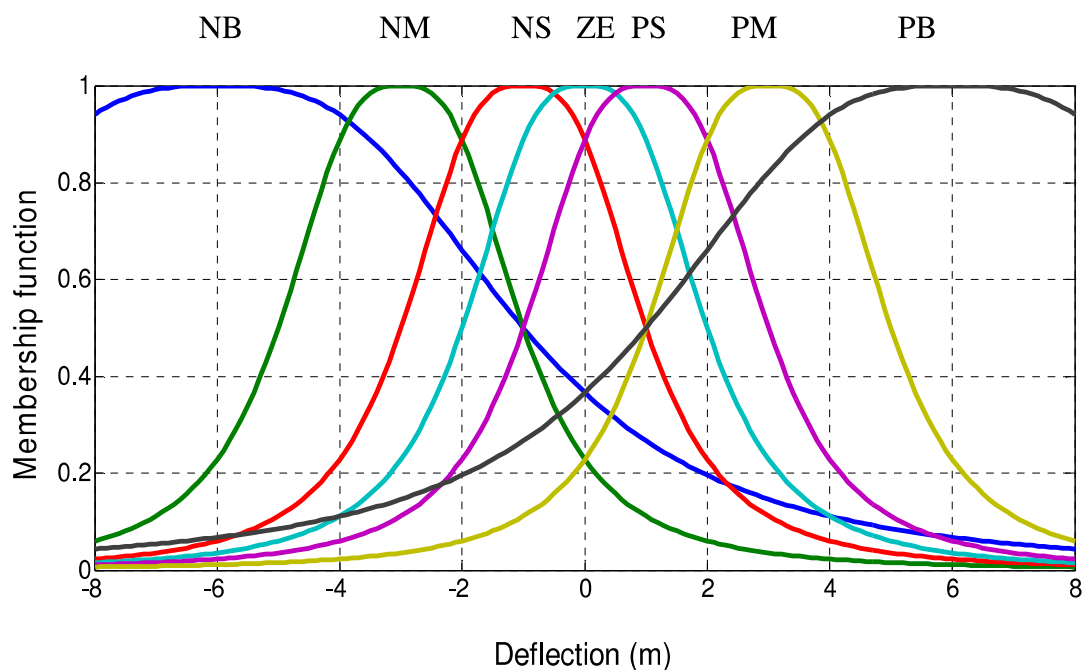


**Figure II.6.a** The membership function of the input variable of the deflection

**II.9.1 .2  The velocity  $x_p$**

**Table. II.1.b**

| | $\{a_i, b_i, c_i\}$ |
|---|---|
| **NB** | $\{2.0, 1.5, -6.0\}$ |
| **NM** | $\{2.0, 1.5, -3.0\}$ |
| **MS** | $\{2.0, 1.5, -1.0\}$ |
| **ZE** | $\{2.0, 1.5, 0.0\}$ |
| **PS** | $\{2.0, 1.5, 1.0\}$ |
| **PM** | $\{2.0, 1.5, 3.0\}$ |
| **PB** | $\{2.0, 1.5, 6.0\}$ |

**Table II.1.b**  The parameters of  the membership function of the velocity  $x_p$
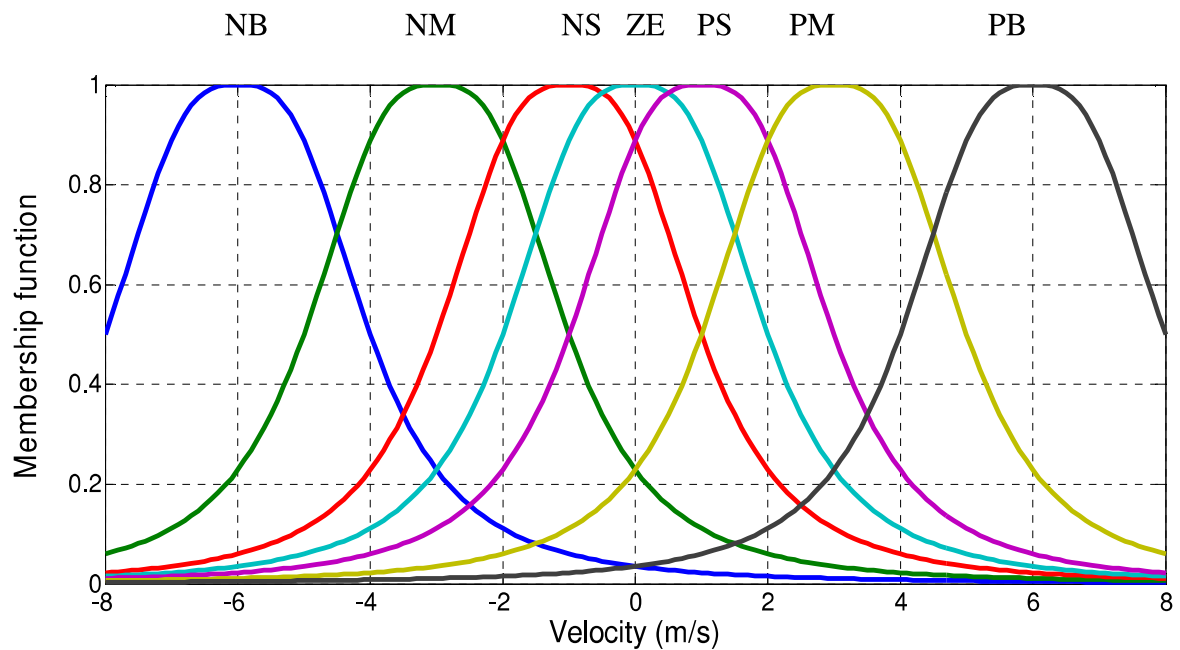


**Figure  II.6.b**  The membership function of the input variable of the velocity

**II.9.1 3.The force  U**

**Table. II.1.c**

| | $\{a_i, b_i, c_i\}$ |
|---|---|
| **NB** | $\{5.0, 1.5, -37.5\}$ |
| **NM** | $\{2.0, 1.5, -25.0\}$ |
| **MS** | $\{2.0, 1.5, -12.5\}$ |
| **ZE** | $\{2.0, 1.5, 0.0\}$ |
| **PS** | $\{5.0, 1.5, 12.0\}$ |
| **PM** | $\{5.0, 1.5, 25.0\}$ |
| **PB** | $\{5.0, 1.5, 37.5\}$ |

**Table  II.1.c**  The parameters of  the  membership function of the force u
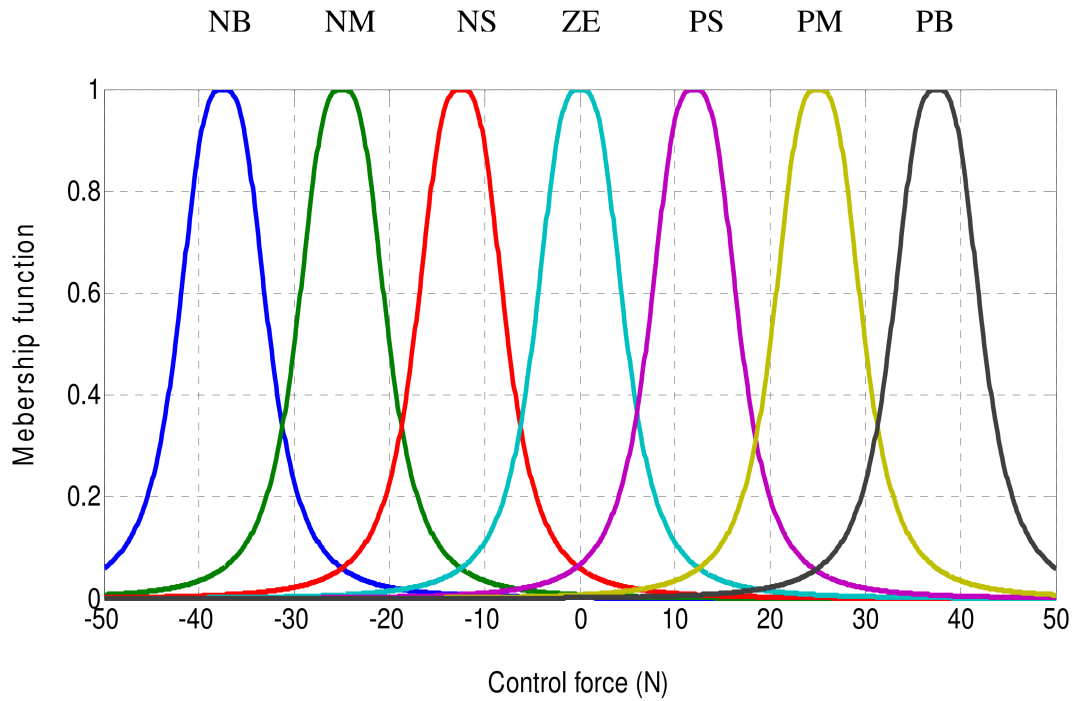


**Figure II.6.c**  The membership function of the output variable of the control force

**Comparison of the membership function of the input and output variables**

➢ The deflection , the velocity and the control force of the membership function  of the input and output variables represented  by the figures .II.4.a ,II.4.b.II.4.c .thanks to the control of fuzzy logic .

➢ The figures II.4.a ,II.4.b we see the membership function of the input has always the same shape.

➢ Fuzzy logic system (FlS) can be defined as the non-linear system of an input set data  to scalar output data.

➢ The membership function is always limited to between 0 and 1, also known as a membership value or membership grade.

➢ The deflection and the velocity of suspension  mass we associated the linguistic terms {NB, NM, NS, ZE, PB, PM, PS}, and control force u defined in this typical case on the interval [-50,50] . As for the variable of output  represent by the force ,we taken only seven fuzzy subsets {NB, NM, NS, ZE, PB, PM, PS} defined on a control force ranging from [-8 8] .

➢ All two-input single-output (TISO) models observe the same assumptions and identical constrains. Similar characteristics of membership function are discussed in this chapter, including overlap ratios between membership functions, the shape of membership functions and the quantity of membership functions for describing a single input variable or output variable [15].

## II.9.2  Base of the rules

The block of control is made of a set of linguistic rules binding the variables of input  to the variables of output, of the type  **IF** {condition}; **THEN** {sequence} **[8]** .

The rules  of  inference  influence  directly  the control  generated  by  the regulator.  The wise choice  of these rules is essential for the good performance of the regulator.

The base rules applied to our controller by fuzzy logic is given by the Table **II.2 [9]**

**Table II.2** Base rules for the controller by fuzzy logic

**Velocity  $\dot{x}$   (m/s)**

|  | | NB | NM | NS | EZ | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| | **NB** | NB | NB | NM | NS | NS | NS | ZE |
| | **NM** | NB | NM | NS | ZE | NS | ZE | PS |
| | **NS** | NM | NS | ZE | ZE | ZE | PS | PM |
| **Deflection $x_p$ (m)** | **ZE** | NM | NS | ZE | ZE | ZE | PS | PM |
| | **PS** | NM | NS | ZE | ZE | ZE | PS | PM |
| | **PM** | NS | EZ | PS | ZE | PS | PM | PB |
| | **PB** | EZ | PS | PS | PS | PM | PB | PB |

The rules which this table describes are (form symbolic system)

**If**   (deflection is NB)  and   (velocity is NB )   **then**  (control-force is NB)

**If**   (deflection  is  NB)  and   (velocity is NM )  **then**  (control-force is NB)

**If**   (deflection  is  NB)  and   (velocity is NS )   **then**  (control-force is NS)

**If**   (deflection  is  NB)  and   (velocity is EZ )    **then**  (control-force is NS)

The control of output     $u$     at every moment  **t**  is given by

$$u\big(u(t)\big) = F\left[u\left(GE.x_p(t)\right), u\left(GC.\dot{x}_p\ (t)\right)\right]$$
(II.4)

With

$F$ =Relation between the parameters of input and output which is defined by the rules of inference.   For our regulator we will use the method of inference **max-min.**

In general it is made use of the one of the following methods

- Method of inference max-min
- Method of inference max-prod
- Method of inference sum-min

## Conclusion

The theory of fuzzy logic  or  the application of a FLC  (Fuzzy logic to control)  is one  very effective  and simple means of use to optimize the control of  the active suspensions using  the fuzzy  rules and variables  and with   the programming   under   the software   MATLAB using Toolbox Fuzzy logic.

# Chapter III:

# Simulation of an active suspension to a degree of freedom

## III.1  Introduction

In  this chapter we  present diagrams of  the  dynamic equations of  sky-hook  model , the active  and  passive  suspension  of  a  degree freedom  of  the  quarter  vehicle, we excite  the system   with   functions of   sinusoidal    and   echelon    road    profile, we  register the performance  criterion using  the software  MATLAB  using  Toolbox     fuzzy logic .

The Fuzzy Logic Toolbox is designed to work seamlessly with simulink, the simulation software available from the math works. Once you have created your fuzzy system using the GUI  tools  or  some  other  method,  you  are  ready  to  embed  your  system  directly  into a simulation [15] .

At the end of chapter will be compared the active  and  passive  suspension  compared  to  the sky-hook  reference model, of each model we present each time the following parameters:

- The acceleration of the body of vehicle    $\ddot{z} = \ddot{x} + \ddot{w}$
- The  deflection of the body of vehicle    $z = x + w$
- Deflection of wheel   $x = z - w$
- Control force

.

## III.2  The parameters  of suspension

The values of the mass,  of  the coefficients of  stiffness and damping,  allotted  to the systems of  passive  suspensions,  Sky-Hook  and active,  refer to work of  M.V.C.Rao and  V.Prahlad [9].

### III 2.1 The parameters  of  suspension and sky-hook reference

The parameters of the   active, the passive suspension and   the   model of the   skyhook reference, show in Table II.1.

**Table III.1** The parameters  of the active, the passive suspension and the sky-hook reference

| System | The parameter | Symbol | Value | Unit |
|--------|---------------|--------|-------|------|
| Active | masse of suspension | $m_m$ | 355 | kg |
| | spring coefficient | $b_m$ | 1 860 | Ns/m |
| | damping coefficient | $k_m$ | 14 384 | N/m |
| Passive | masse of suspension | $m_b$ | 355 | kg |
| | spring coefficient | $b_b$ | 1 860 | Ns/m |
| | damping coefficient | $k_b$ | 14 384 | N/m |
| Sky-hook | masse of suspension | $m_p$ | 355 | Kg |
| | spring coefficient | $b_p$ | 3 000 | Ns/m |
| | damping coefficient | $k_p$ | 15 000 | N/m |

### III 2.2  The Profits used

**GE**=10,    **GC**=1,    **GU**=300.

## III.3  The Flow chart of simulation

The  Flow   chart below   illustrates the course of the   digital resolution of   the differential equation.

The  loop  will  be  carried out  until  time reaches  **t =5  sec**.  The interval  or  increment of calculation is of  **0.01 sec** . More  the increment  is  small plus the pace of continuity and the precision of  the graphs is visible .
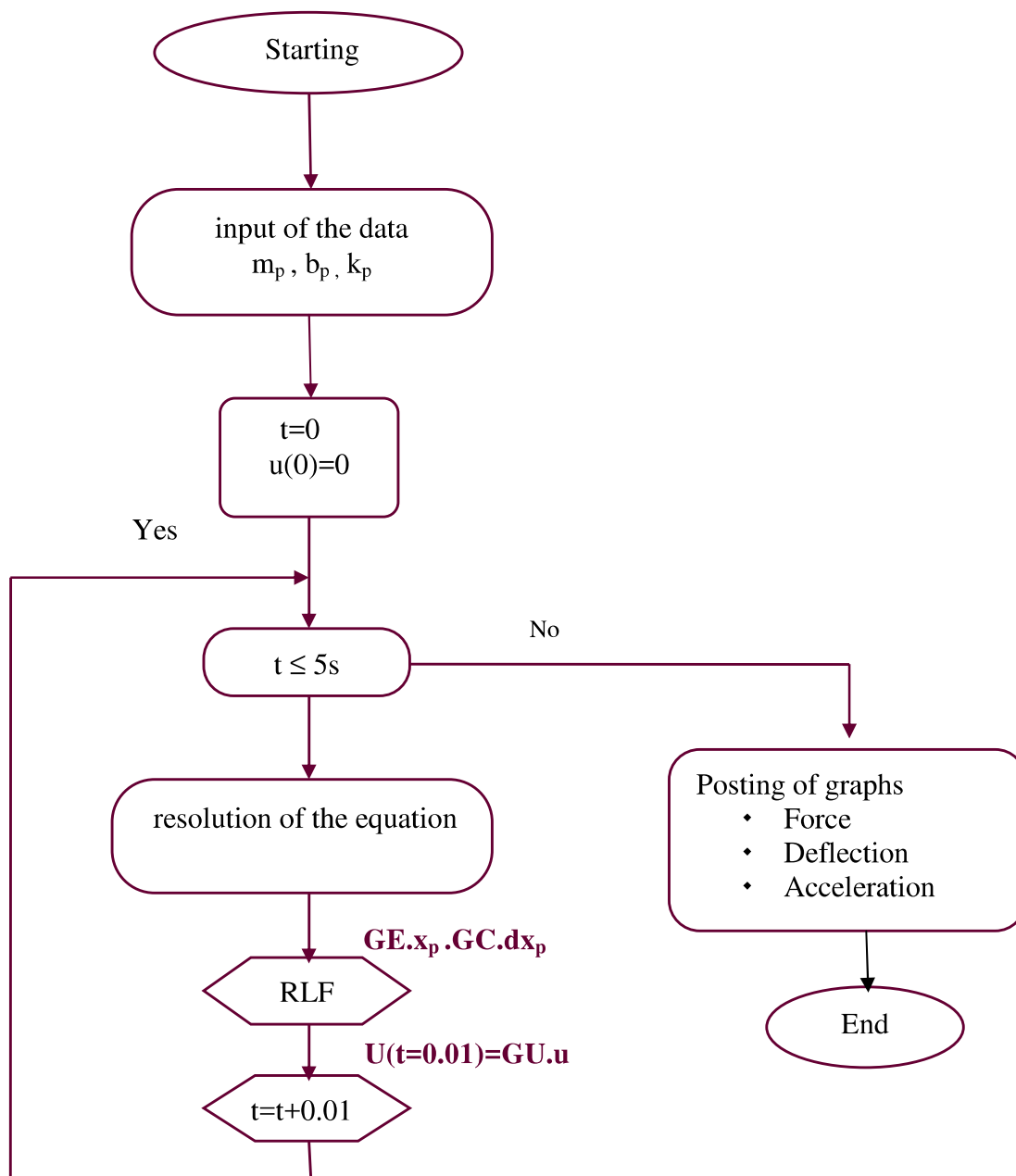
### III.4 Response of the system to a sinusoidal road profile input

### III 4.1 Profile of the sinusoidal road (disturbance)

The inputs used are illustrated below:

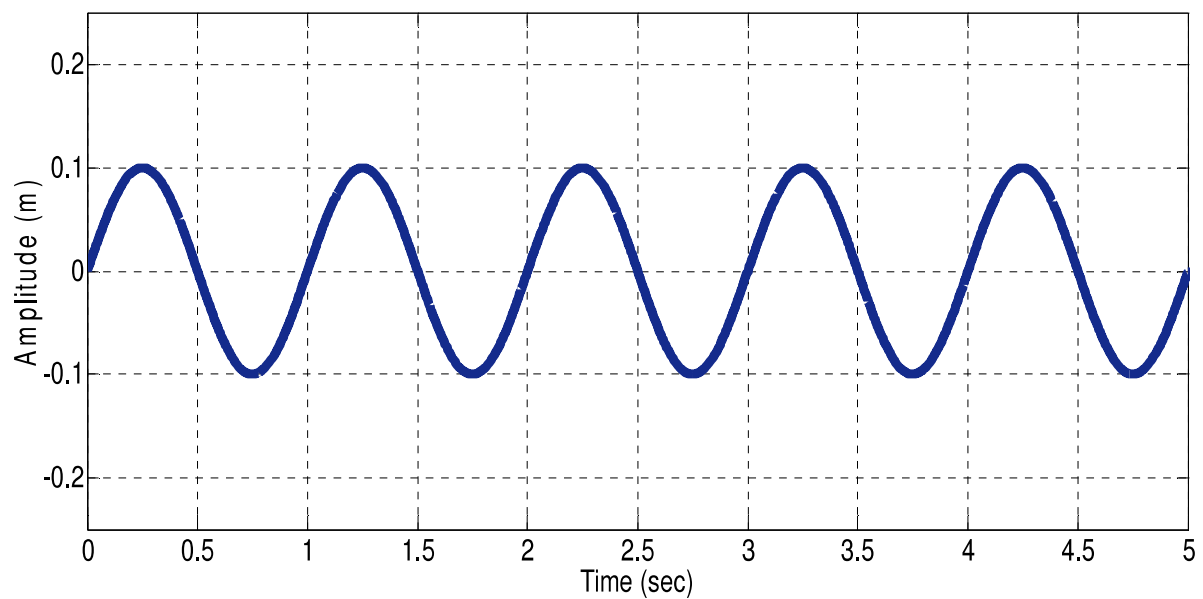The results are obtained for sinusoidal input at t = 5 sec, and an amplitude of 0.1m.



**Figure III.2** Sinusoidal input

The equation of the pseudo-random input is written

$$W = 0.1 \sin (2\pi t) \tag{III.1}$$

### III 4.2 Simulation of sky-Hook model

The simulation of the resolution of the dynamic equation of the sky--hook model is carried out using the simulink of the Matlab environment [10].
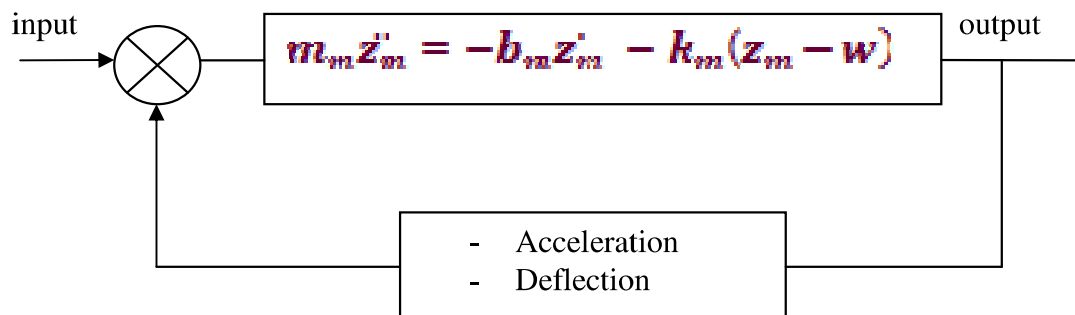


$$m_m z_m^{\cdot\cdot} = -b_m z_m^{\cdot} - k_m(z_m - w)$$

**Figure III.3.a** Functional Schematic of the sky-hook model
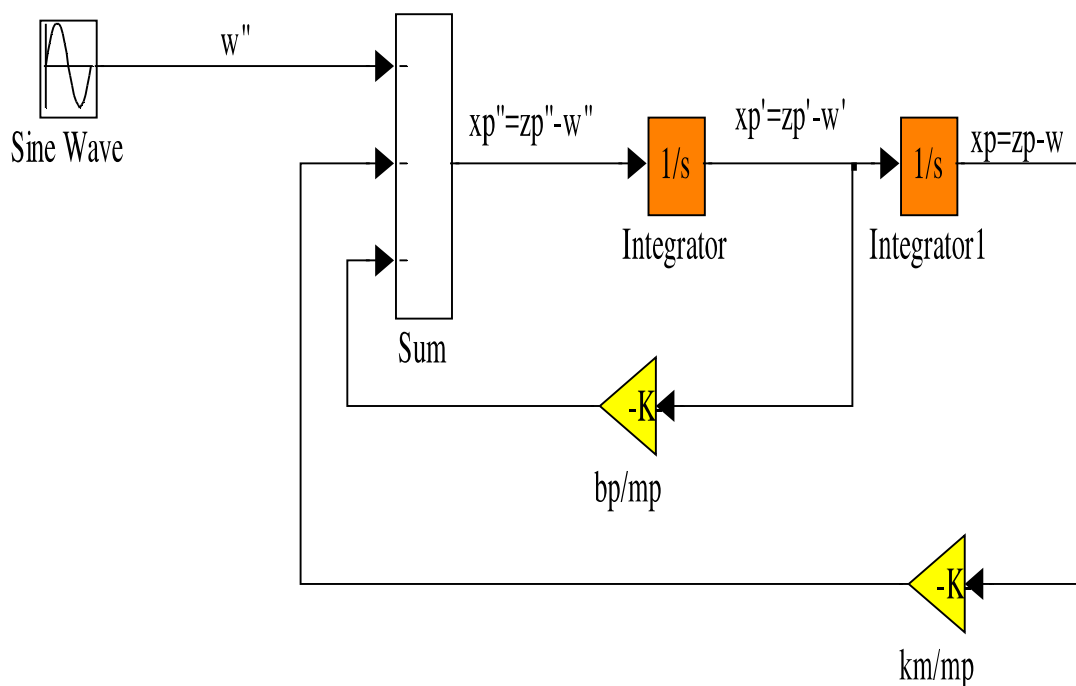


**Figure III.3.b** Functional diagram for the sky_hook model of simulink

### III 4.3  Simulation of  passive suspension

The simulation of  the resolution of the  dynamic equation of  the passive suspension  model is carried out using the simulink of  the  Matlab  environment  [10].



input  road                                                                                          force

$$m_m \ddot{z}_m = -b_m \dot{z}_m - k_m(z_m - w)$$

- Acceleration
- Deflection

**Figure III.4.a** Functional  Schematic  of the passive suspension



zb"= xb"+w"

Sine Wave          w"          xb"=zb"-w'          xb'=zb'-w'          1/s          xb=zb-w

Integrator 1          Integrator 2

Sum          -K          bb/mb          -K          kb/mb

**Figure III.4.b** Functional diagram for the  passive model of  simulink

## III.4.4  Simulation of  active  suspension

The simulation of  the resolution of the  dynamic equation of  the active  suspension  is carried out using the simulink of  the  Matlab  environment  [10].
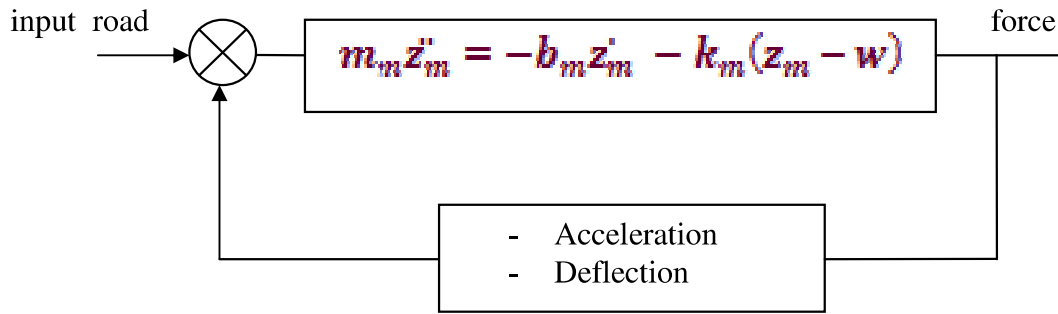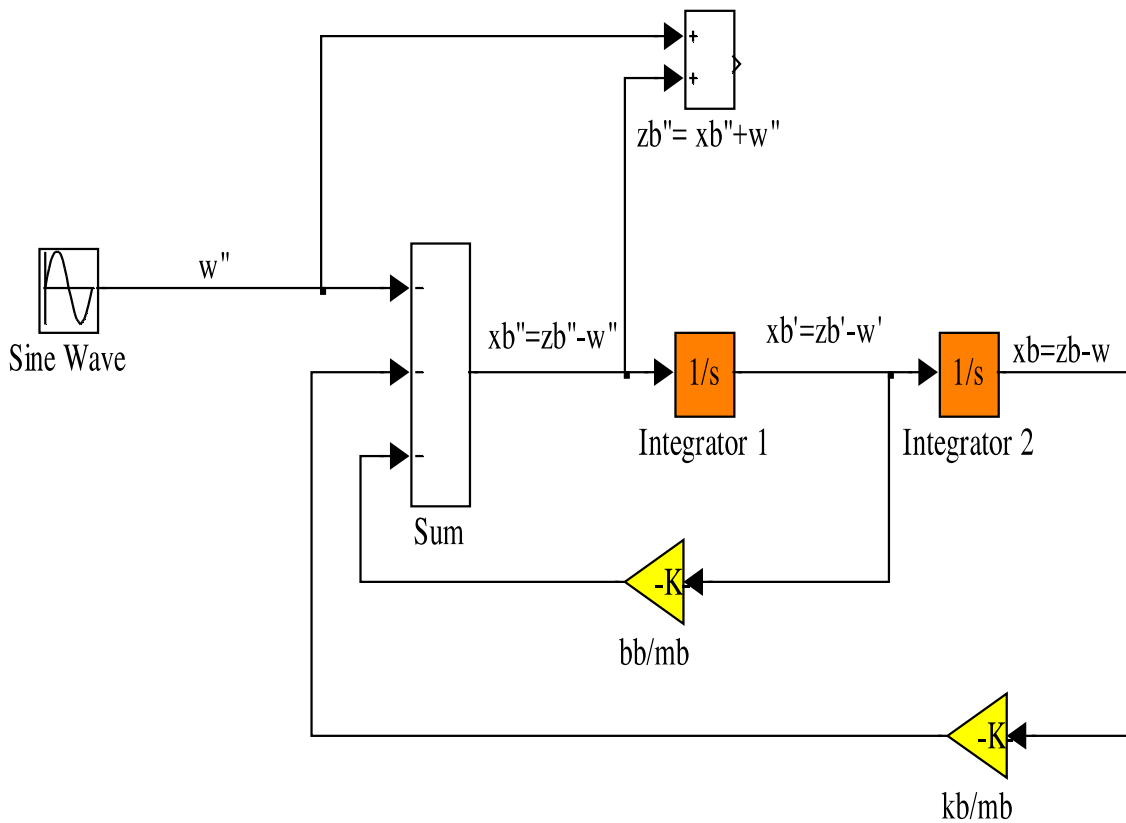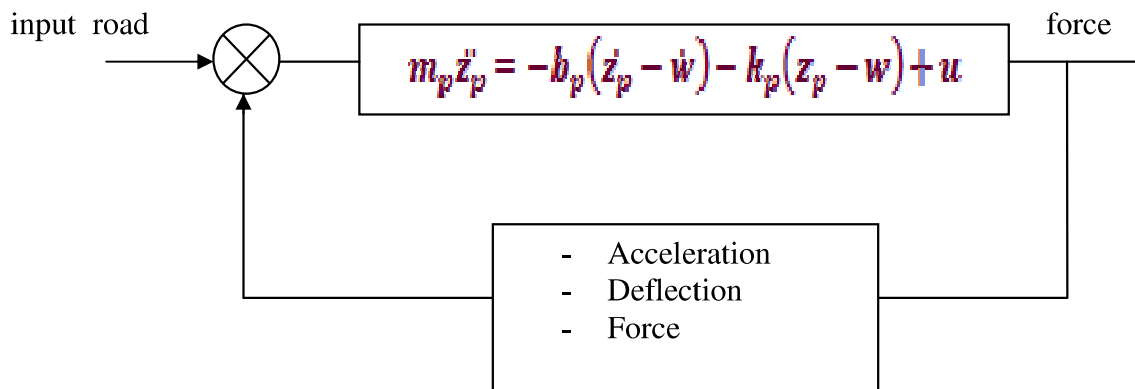


$$m_p \ddot{z}_p = -b_p\left(\dot{z}_p - \dot{w}\right) - k_p\left(z_p - w\right) + u$$

**Figure III.5.a** Functional Schematic of the  active suspension



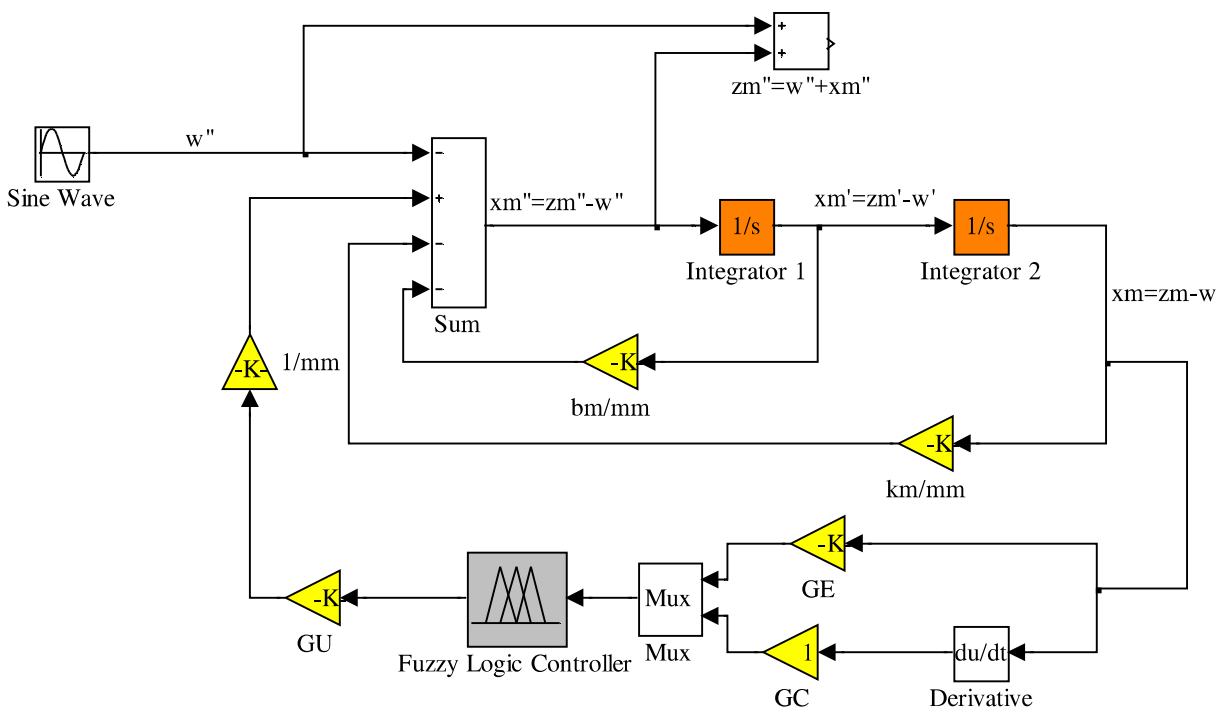**Figure III.5.b** Functional diagram for active model of  simulink

## III 4.5 Compared of the passive  suspension  with  the  sky-hook model   of .

.                                     reference

### III 4.5.1 Acceleration of  the body of vehicle

Figure II.6.a gives us a comparison,  the acceleration  of  the body of  vehicle between  the passive suspension  and the sky-hook model of reference .
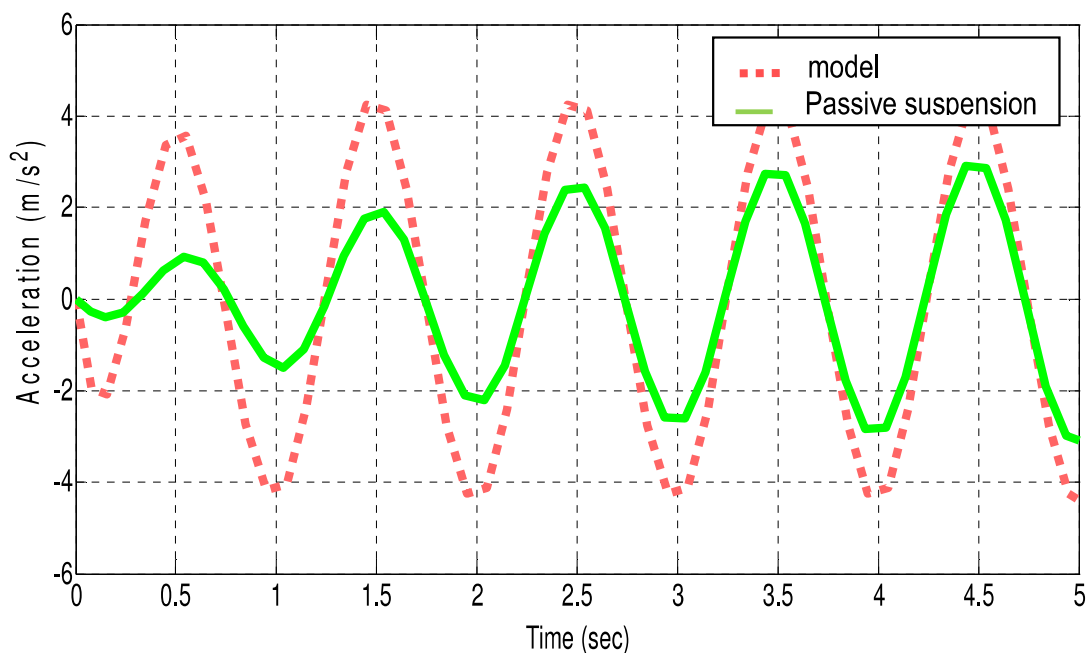


**Figure III 6.a** Acceleration

The accelerations of the  body of   vehicle of the passive suspension lower than acceleration of sky-hook  model  of  reference , as well as   in acceleration of the  body of vehicle the minimum value  of amplitude  1m and the  minimum value of amplitude   1 m , which enables us to conclude the passive suspension  is most powerful .

**III 4.5.2 Deflection of wheel**

As for the figure.II.6.b  it compares the deflections of wheel between the passive suspension and the sky-hook mode of reference
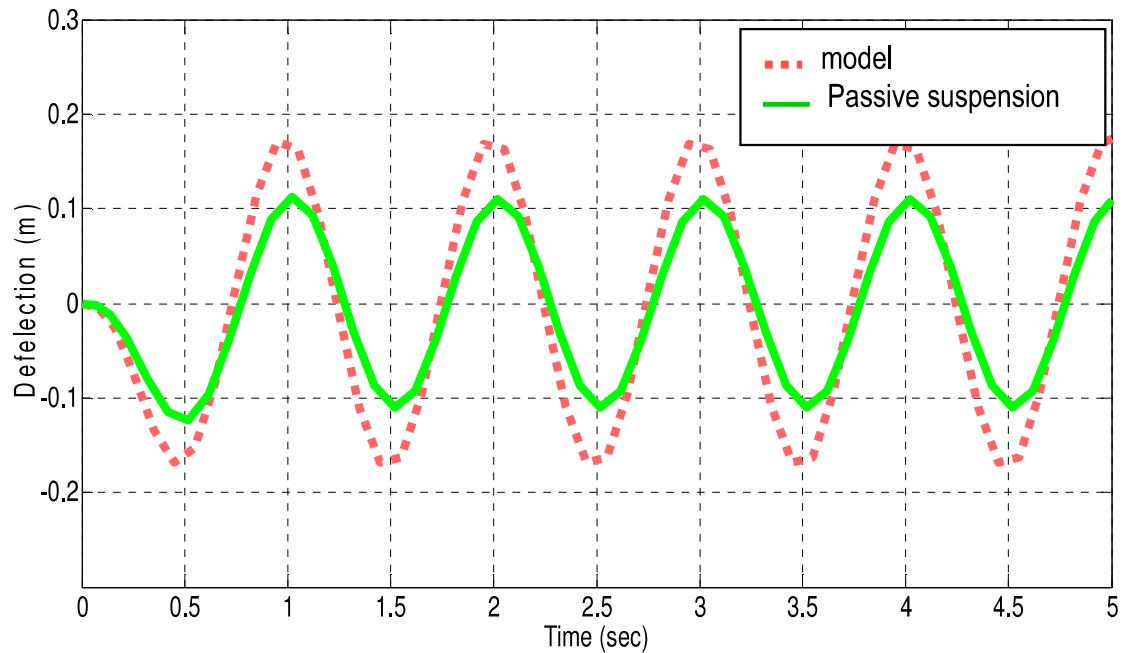


**Figure III.6.b** Deflection

we can see that the deflection of wheel of the passive suspension lower than the deflection of wheel of sky-hook model of reference , as well as  in deflection of wheel  the maximum value  of amplitude  0.1 m  and the  minimum value of amplitude   -0.1 m , which enables us to conclude the passive suspension  is most powerful .

.

## III 4.6 Compared the active suspension with the sky-hook model of reference

**III 4.6.1 Acceleration of the body of vehicle**

The figure .II.7. a   gives us a comparison  the acceleration of the body of vehicle between the active  suspension  and  the sky-hook model of reference .
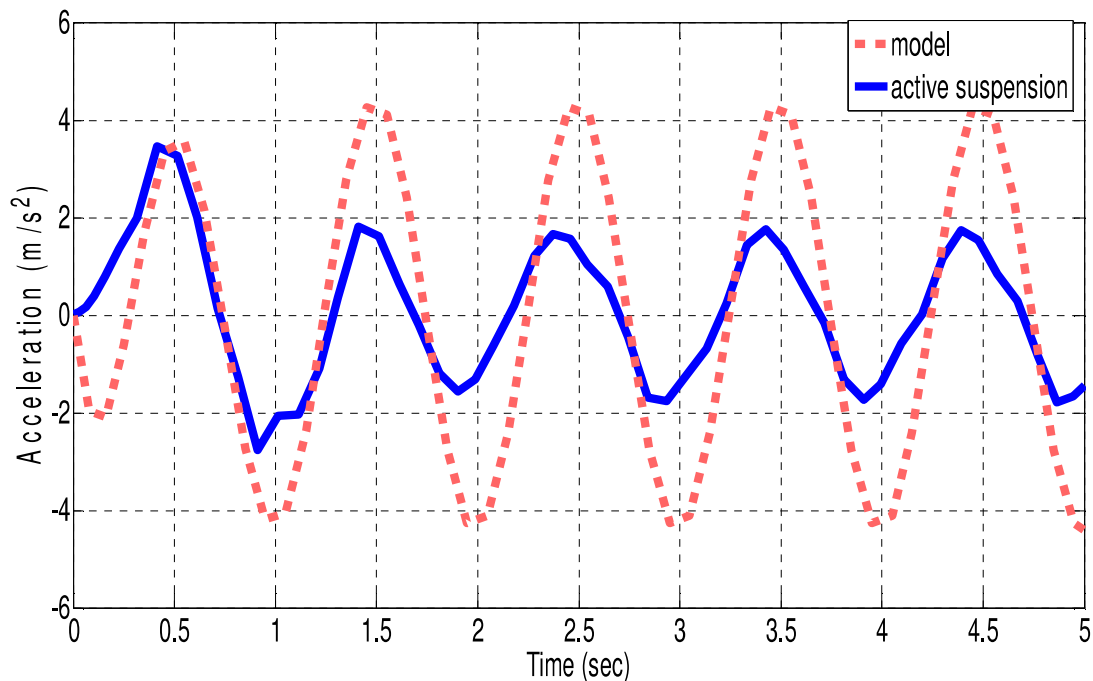


**Figure III .7.a** Acceleration

The  accelerations  of  the   body of    vehicle  of  the  active   suspension  lower  than  the acceleration of the  body of   vehicle of  the sky-hook model of reference  .The aim is to achieve   small amplitude value for active  suspension  for improve a better  ride  comfort .

**III 4.6.2 Deflection of wheel**

The figure.II.7.b it compares the deflections of wheel between the passive suspension and the sky-hook model of reference.
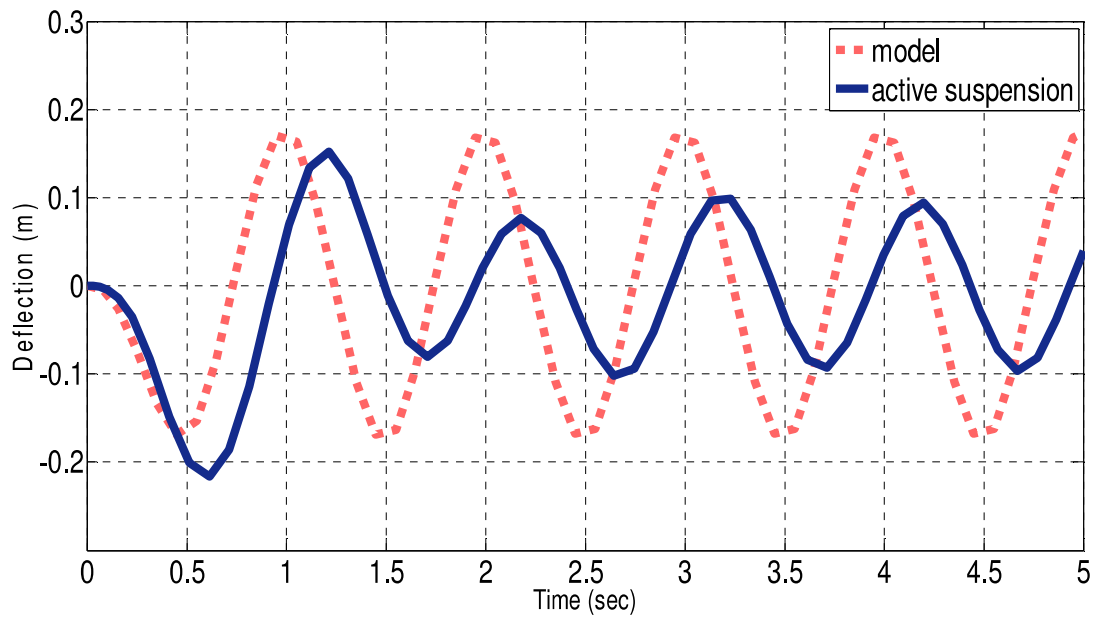


**Figure III .7.b** Deflection

The deflection of wheel of the active suspension lower than the deflection of the wheel of the sky-hook model of reference, the aim is to achieve small amplitude value for the active suspension for a better road holding .

### III 4.6.3 Control force

The figure III.7.c represents the control force of active suspension  thanks to  the Controller by fuzzy logic, for following profits  GE=10,  GC=1,    GU=300 .
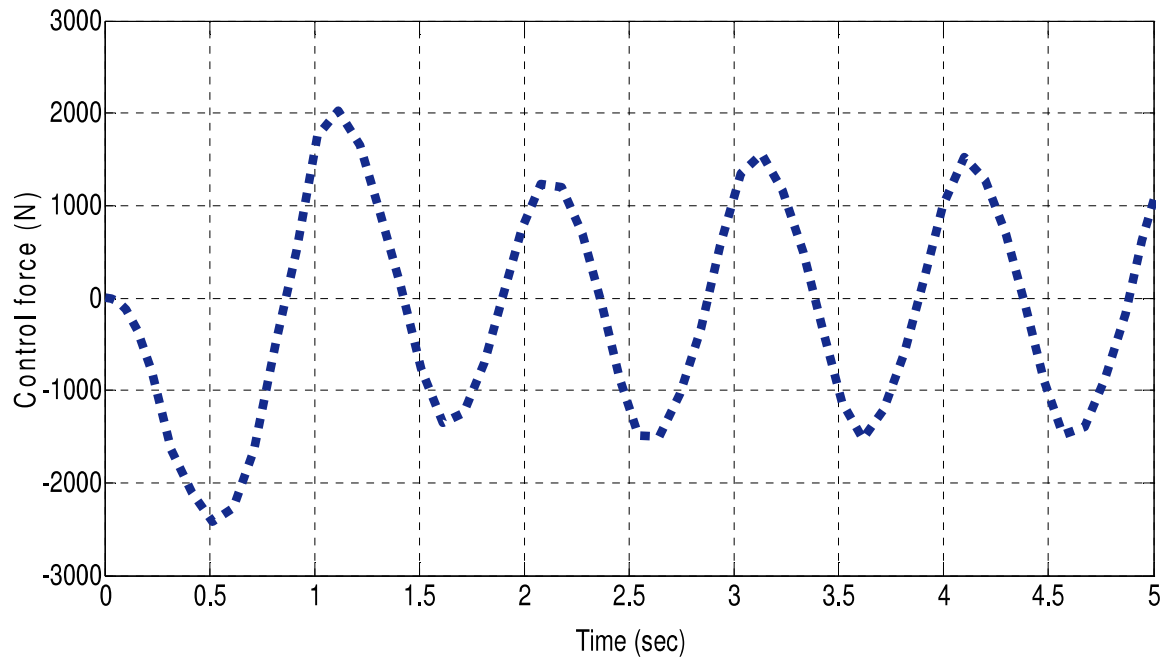


**Figure III.7.c**  Control force

The value of amplitude of the control force is limited between [2000  ,-2000 ], so the active suspension system has good performance because the control force using feedback to improve system response .

### III.5  Response of the system to an echelon  road profile input

### III 5.1 Profile of the echelon  input  (disturbance)

The inputs used are illustrated below:

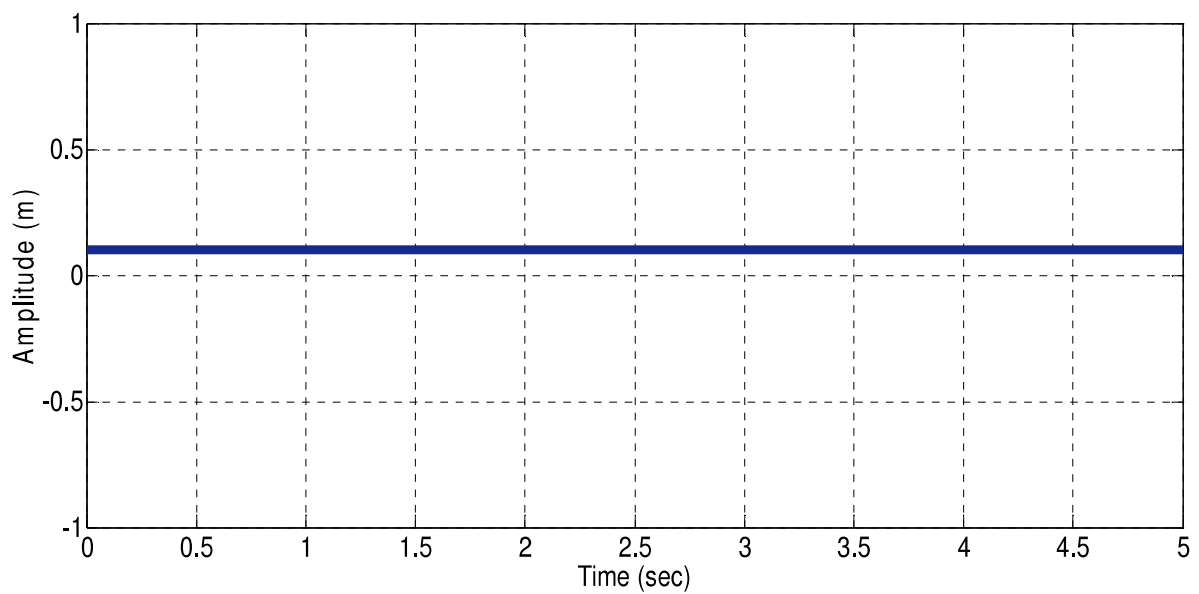The results are obtained for an echelon  input  at  t = 5 sec, and an amplitude of  0.1 m.



**Figure III.8** Echelon input

## III 5.2 Simulation of active model

The simulation of the resolution of the dynamic equation of the active suspension is carried out using the simulink of the Matlab environment [10].

input road                                                                    force

$$m_p \ddot{z}_p = -b_p \left( \dot{z}_p - \dot{w} \right) - k_p \left( z_p - w \right) + u$$

- Acceleration
- Deflection
- Force

**Figure III.9.a** Schematic of the active suspension for simulink
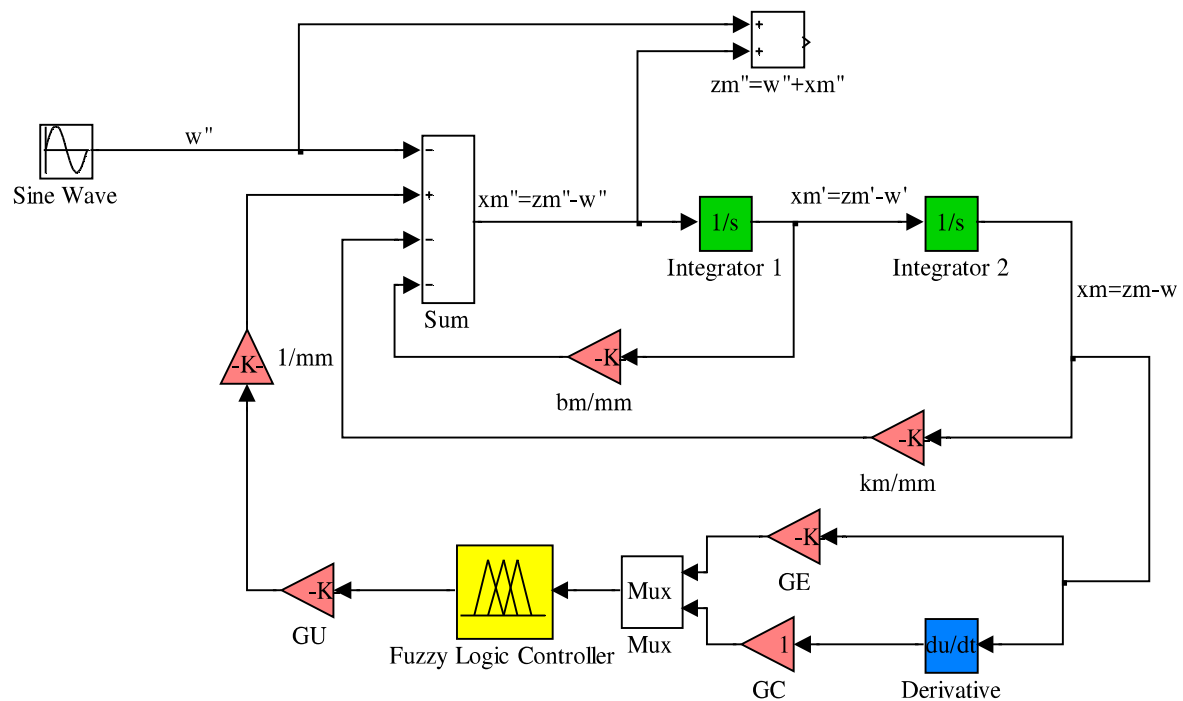
**Figure III.9.b** Functional diagram for active model

## III 5.3  Simulation of passive suspension

The simulation of the resolution of the dynamic equation of the sky--hook model is carried out using the simulink of the Matlab environment [10].

Input road

$$m_m \ddot{z}_m = -b_m \dot{z}_m - k_m(z_m - w)$$

force

- Acceleration
- Deflection

**Figure III.10.a** Schema of the passive suspension for simulink



**Figure III.10.b** Functional diagram for the passive model

## III 5.4 Simulation of sky-Hook model

The simulation of the resolution of the dynamic equation of the passive suspensionis carried out using the simulink of the Matlab environment [10].
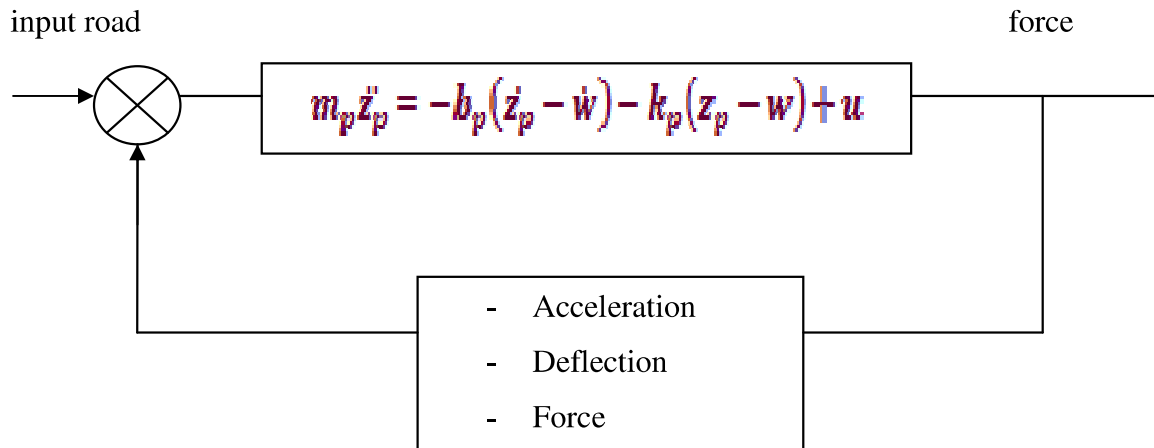
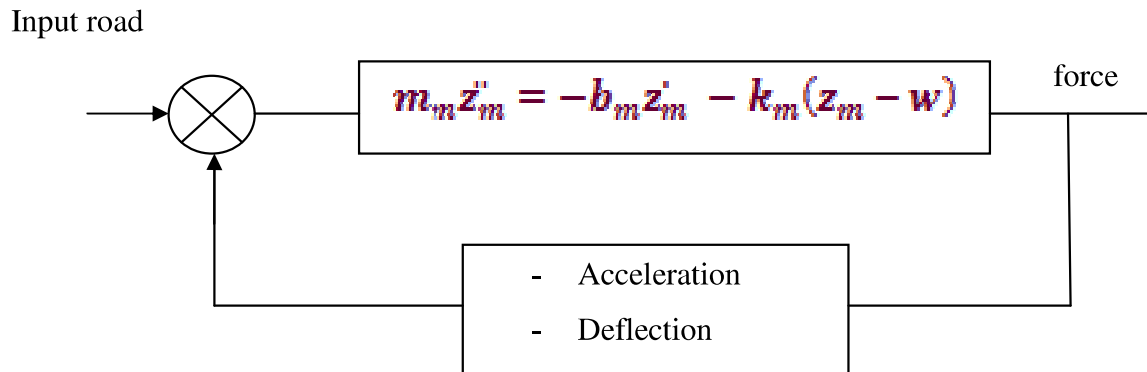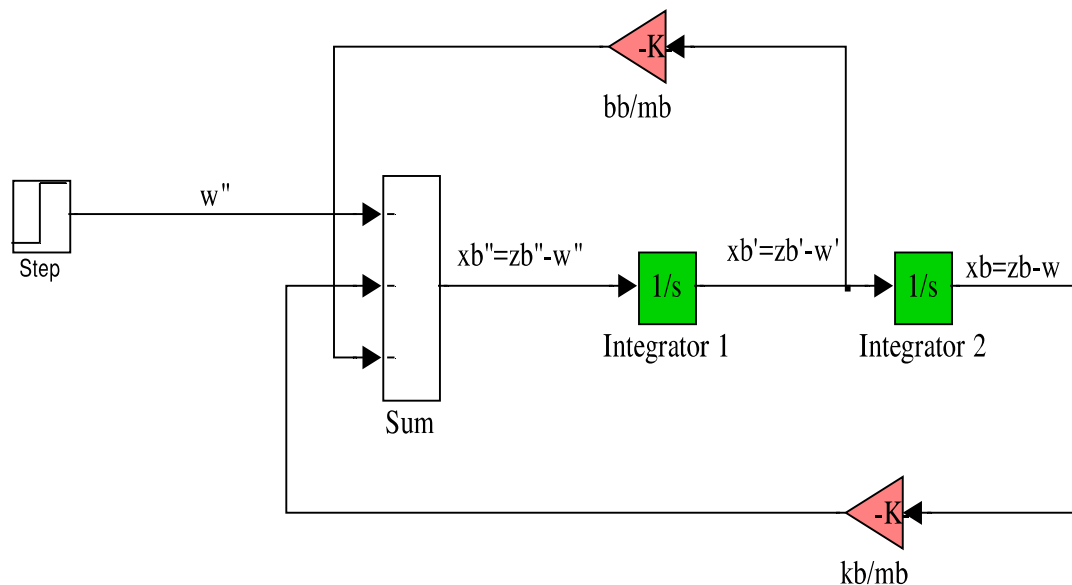Input road                                                                                                          force

$$m_m \ddot{z}_m = -b_m \dot{z}_m - k_m(z_m - w)$$

-  Acceleration
-  Deflection
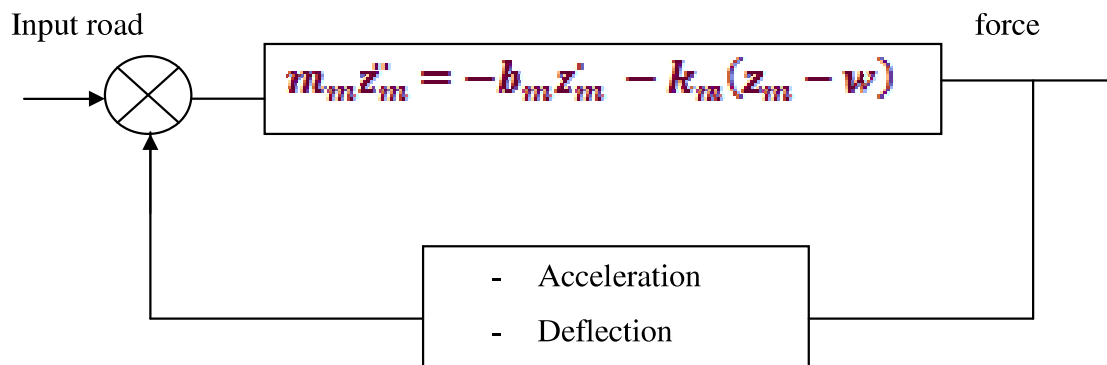
**Figure III.11.a**  Schema of the passive suspension for simulink

Step    w"

bp/mp    -K

xp"=zp"-w"    1/s    xp'=zp'-w'    1/s    xp=zp-w

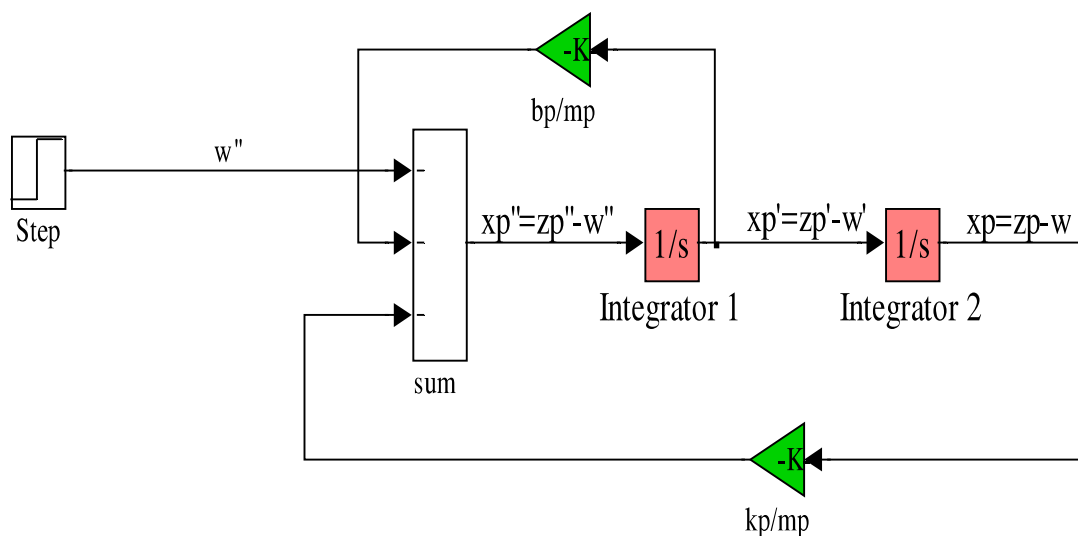Integrator 1    Integrator 2

sum

-K    kp/mp

**Figure III.11.b** Functional diagram for the sky_hook model

## III 5.5 Compared the passive and the active   suspension   with to the model of reference

**III 5.5.1 Acceleration of  the body of vehicle**

Figure II.12. a  gives us a comparison,  the acceleration  of  the body of vehicle  between  the passive  and the  active suspension   with the sky-hook model of reference  .
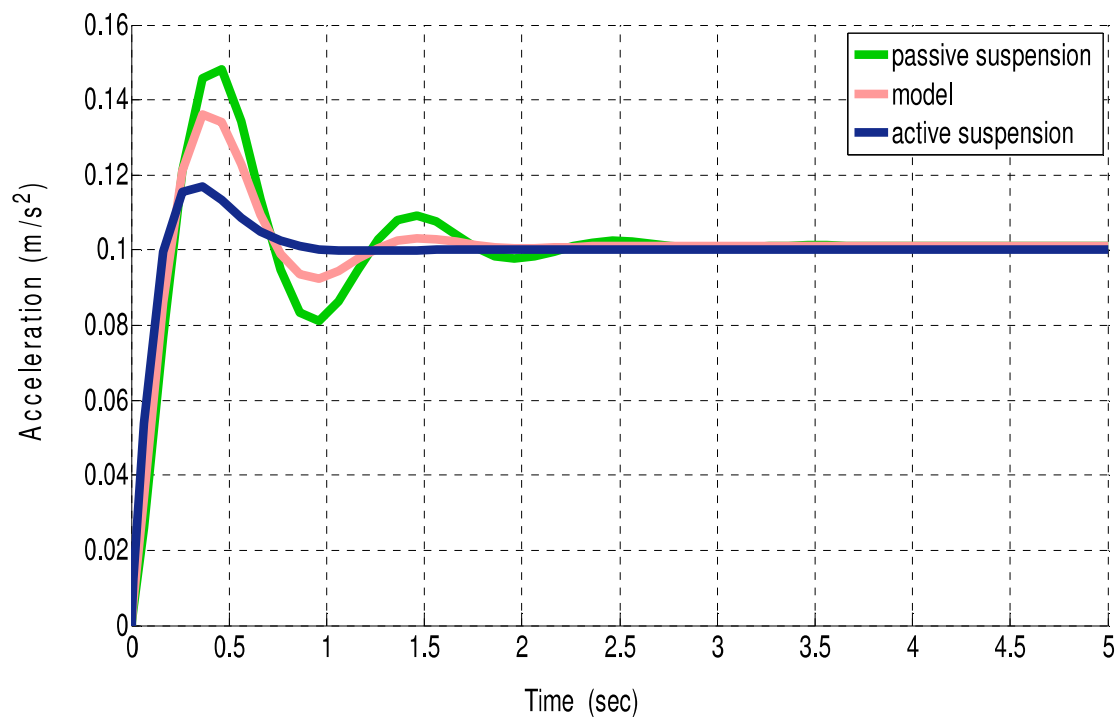


**Figure III.12.a**  Acceleration

In  the  figure  shows  clearly  that  the  acceleration  of  the  body  of  vehicle   much  lower  than passive suspension  and  sky hook model of reference   because  the amplitude of acceleration of the body of vehicle of active suspension less than amplitude of acceleration of the body of vehicle of other systems .

**III 5.5.2 Deflection of wheel**

Figure II.12.b gives us a comparison, the deflection of the wheel between the passive suspension and the active suspension with the sky-hook model of reference .
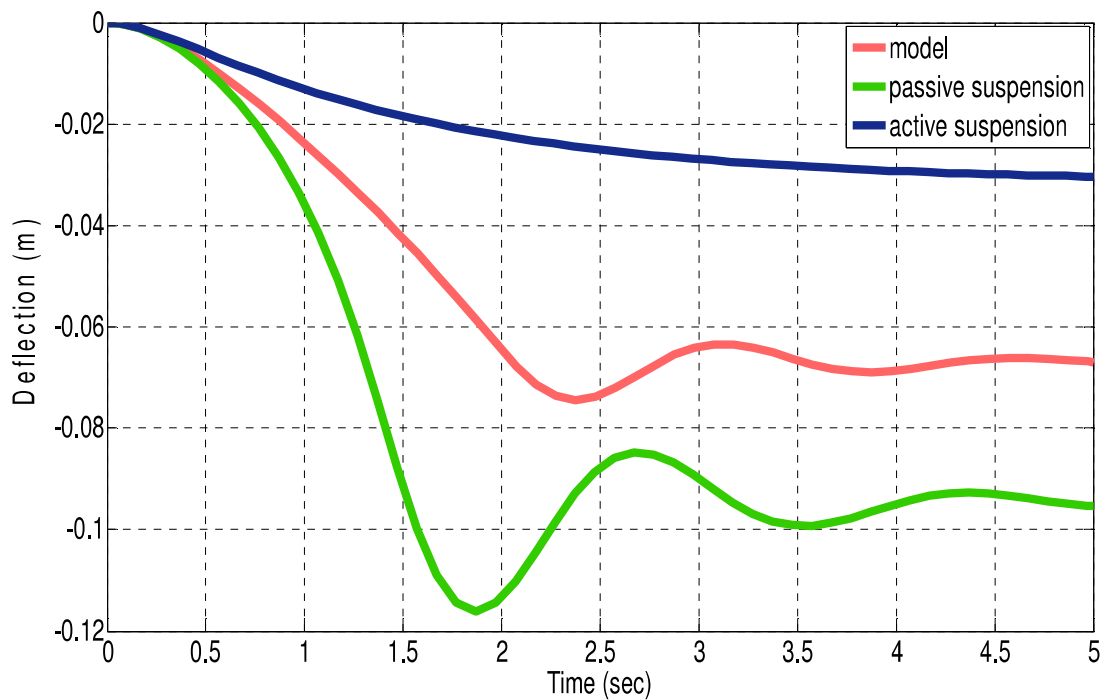


**Figure III.12.b** Deflection

In the figure shows clearly that the deflection of wheel of active suspension much lower than passive suspension and sky hook model of reference which means the active suspension reduce the vibration .

**III 5.5.3 Control force**

Figure III.12.c.. represented the control force applied of the active suspension for following profits GE=10, GC=1, GU=300 .
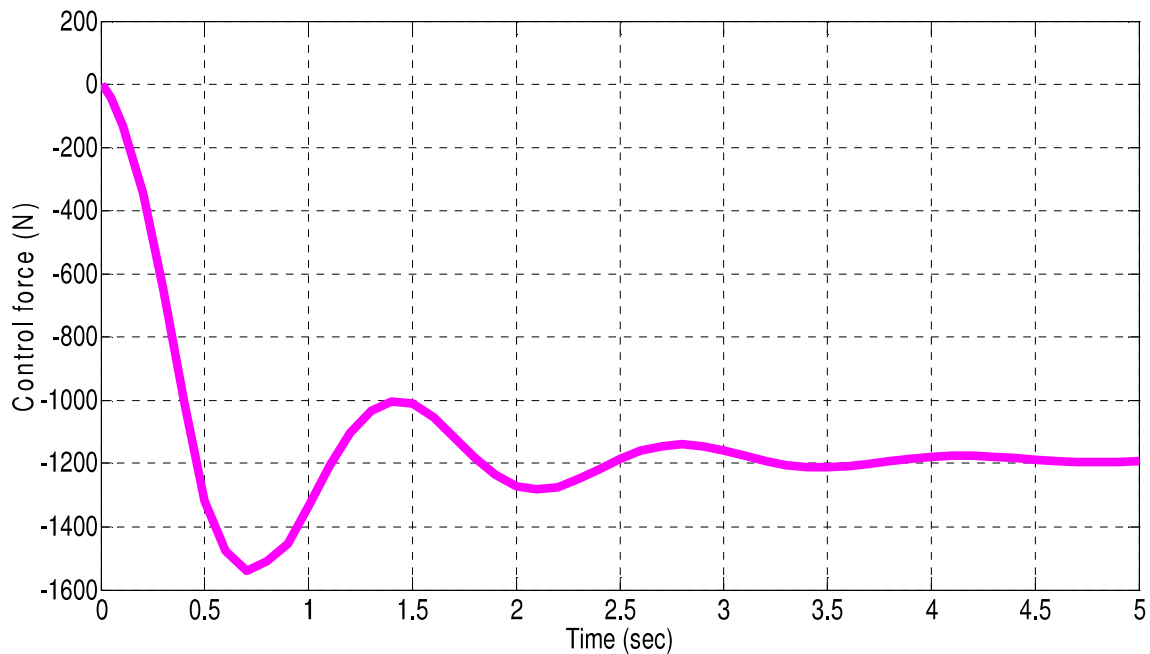


**Figure III.12.c** Control force

The maximum value of amplitude of the control force is in the opposite direction of the motion 100 N , so the active suspension system has good performance because control force using feedback to improve system response .

we clearly see that the active suspension gives a better result than the passive suspension which means that an actuator force to an active suspension reduce the vibration which result in improving the security and the comfort for passenger .

## Conclusion

In this chapter we saw the application of  the  regulation by fuzzy logic in the controlling of  our  system of active suspension. This approach offers  compared  to the classical methods a good amount of  advantages:

- Simple design.
- Flexibility of  its   application and   its good   adaptation  to  the various  systems  of regulation.
- Does not require a knowledge  of  the   mathematical   model  of  the  system  has  to control.

However, the choice of  the   parameters  of  the regulator  (universe of  the discourses , functions  of  memberships…)  remain a  very difficult  task and  the development of the base of  the rules is not always  easy to formulate in  linguistic rules.  It is hard, because it depends much on  human  expert  testimony.

# General conclusion

The methodology was developed to design an active suspension for a passenger vehicle by designing a controller, which improves performance of the system with respect to design goals compared to passive suspension system. Mathematical modeling has been performed using a  degree of freedom model of the quarter vehicle model for passive and active suspension system considering only pump  motion to evaluate the performance of suspension with respect to various contradicting design goals.

Fuzzy logic controller design approach has been examined for the active system suspension travel in active case has been found reduced. By including an active element in the suspension, it is possible to reach a better compromise than is possible using purely passive elements. The potential for improved ride comfort and better road handling using  fuzzy logic controller design is examined. The objectives of this project have been achieved. Dynamic model for linear quarter vehicle suspensions systems has been formulated and derived only one type of controller is used to test the systems performance which is fuzzy logic controller .

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