A REVIEW WORK ON SUSPENSION SYSTEMS MODELS, CONTROL STRATEGIES FOR SUSPENSION SYSTEM

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Abstract*— Ride comfort and handling performance of vehicle is contributed by suspension system in vehicle dynamics. There are different aspects which describe vehicular dynamics and ride comfort and handling performance but suspension system majors. Passive suspension, semi active suspension and active suspension have greater performance, suspension performance is understood by quarter car model with two three degrees of freedom at each of wheels, half car model with four degrees of freedom viz, roll degree of freedom and pitch degree of freedom. And full car model with seven degrees of freedom four degrees at sprung masses and three degrees at sprung masses. Quarter car model is more researched since model is simple, as degrees of freedom increases complexity increases. After comparative comprehensive studies, it is deduced that electromagnetic active suspensions are the future trend of automotive suspensions due to simple structure, high-bandwidth, accurate and flexible force control, high ride quality, good handling performance, and energy regeneration.

Keywords: - Suspension System, Passive, Semi active, Active Suspension, Quarter Car, Half Car, Full Car Model.

I. INTRODUCTION

A 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. Therefore suspension design must be comparison between three conflicting criteria of road holding, load carrying and passenger comfort.[23]

A typical automobile suspension system consists of spring and damper. Every automotive suspension has two goals: passenger comfort and vehicle control. Comfort is provided by isolating the vehicle's passengers from road disturbances like bumps or potholes. Control is achieved by keeping the car body from rolling and pitching excessively, and maintaining good contact between the tire and the road. The role of the damper is to dissipate energy transmitted to the vehicle system by road surface irregularities. In a conventional passive suspension, both stiffness and damping are fixed at the design stage. The choice of the damper is affected by the classic trade-off between vehicle safety and ride comfort. *Ride/Comfort* is ability to smooth out a bumpy road, measurement of ride quality in vehicles is energy input measured at the driver's seat. *Handling* is ability to safely accelerate, brake and corner.

Every automotive suspension has two goals: passenger comfort and vehicle control. Comfort is provided by isolating the vehicle's passengers from road disturbances like bumps or potholes. Control is achieved by keeping the car body from rolling and pitching excessively, and maintaining good contact between the tire and the road. With low damping handling performance is compromise while as damping coefficient value increases ride/comfort is compromised. This trade-off can be only eliminated when damping is varied as per dynamic conditions which are not possible in passive suspension system. This trade-off can be reducing in controlled suspension system.

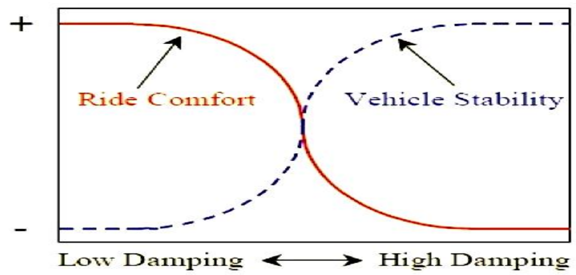


Fig 1 Compromise between Ride and Handling [27]

A heavily damped suspension will yield good vehicle handling, but also transfers much of the road input to the vehicle body.[21] When the vehicle is traveling at low speed on a rough road or at high speed in a straight line, this will be perceived as a harsh ride. The vehicle operators may find the harsh ride objectionable, or it may damage cargo. A lightly damped suspension will yield a more comfortable ride, but can significantly reduce the stability of the vehicle in turns, lane change maneuvers, or in negotiating an exit ramp. Good design of a passive suspension can to some extent optimize ride and stability, but cannot eliminate this compromise. The need to reduce the effects of this compromise has led to the development of active and semiactive suspensions. Active suspensions use force actuators. Unlike a passive damper, which can only dissipate energy, a force actuator can generate a force in any direction regardless of the relative velocity across it. Using a good control policy (here fuzzy loggy), it can reduce the compromise between comfort and stability. However, the complexity and large power requirements of active suspensions make them too expensive for wide spread commercial use. Semiactive dampers are capable of changing their damping characteristics by using a small amount of external power. Semi active suspensions are less complex, more reliable, and cheaper than active suspensions. They are becoming more and more popular for commercial vehicles.

The main function of vehicle suspension system is to minimize the vertical acceleration transmitted to the passenger which directly provides road comfort. There are two aims of vehicle suspensions to provide an isolation of a vehicle body from road irregularities and to ensure good road holding. The first goal lies within the area of ride analysis and concern a problem of how to reduce a discomfort experienced by vehicle occupants. The second one lies within the area of handling analysis. Here, the handling means an ability of a vehicle to safely accelerate, brake and corner with the "ease-of-use" [1-6]. The design goal is to minimize both the acceleration of the body and the dynamic tire load, while operating within the constraints of suspension rattle space for a given suspension parameter set.

The vibration of an on-road vehicle is predominantly excited by the unevenness of the road surface on which the vehicle travels. Vehicle dynamic analysis has been a hot research topic for many years due to its important role in ride comfort, vehicle safety and overall vehicle performance. Numerous papers about the theoretical and experimental investigation on the dynamic behavior of passively and actively suspended road vehicles have been published. The quarter-car model, half-car model and full-vehicle model have been developed with researches related to the dynamic behavior of vehicle and its vibration control. The performance of suspension system can be measured by two values ride comfort and handling which corresponds to acceleration at sprung mass and displacement at unsprung mass.

II.SUSPENSION SYSTEM

Suspension systems are of different types, but generally categories in conventional suspension and advanced suspension systems or controlled suspension systems. Conventional suspension system refers to the passive suspension system whereas advanced suspension system indicates semi-active suspension or active suspension system.

Passive Suspension System

Suspension system at traditional or say conventional suspension system is also known as a passive suspension system. It consisting of spring and damper mounted at each wheels of the vehicle in parallel. The function of spring in vehicle suspension is to support the vehicle body and at the same time it is used to absorb and store the energy. Spring hold vehicle i.e. static load is taken by spring. Stiffness of spring is calculated at its design stage in passive suspension system. The damper or shock absorber is a component of the vehicle suspension used to dissipate the vibration energy stored in the spring and control the input from the road that is transmitted to the vehicle. Damping action i.e. coefficient of damping is selected at design stage and for type of vehicle performance required for ride/comfort or handling. For luxury car ride is the main criterion and for sport utility vehicle handling is the main requirement.

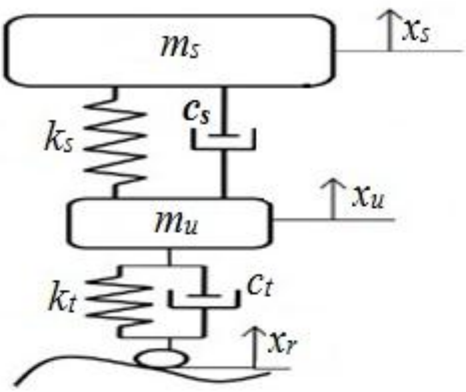


Fig 2 Quarter Car Passive Suspension System.

The passive suspension system is an open loop control system. It only designs to achieve certain condition only. The characteristic of passive suspension fix and cannot be adjusted by any mechanical part. The problem of passive suspension is if it designs heavily damped or too hard suspension it will transfer a lot of road input or throwing the car on unevenness of the road.

Passive suspension cannot perform best ride comfort and handling, it always compromise in it so advanced suspension system or say controlled suspension system came into picture.

Semi Active Suspension System

A semi-active suspension is identical to passive suspension system with only varying damping coefficient and constant spring constant one without active force sources. Thus, the mechanical layout of a semi-active suspension is identical to a passive one. However, some control of damping coefficient can achieve by switching the characteristics of dampers. Consequently, this gives the possibility of the damper reaction forces. A semi-active suspension can be remotely electrically switched to either soften or stiffen the suspension. Its damping coefficient can be changed continuously or discontinuously.

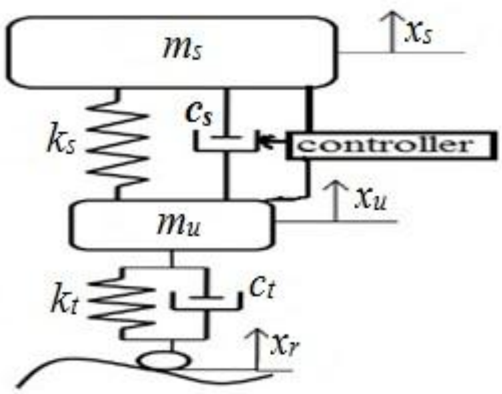


Fig 3 Quarter Car Semi-active Suspension System

For large road wheel movements, moreover, it is often used to switch from the soft to hard settings to prevent crash-through of the suspension on irregular road surfaces. The soft setting is restored after a few seconds of fairly straight and constant speed driving. It can be seen that semi-active suspensions operate under closed-loop control.[17][20] An example of a commercial electromagnetic damper (Magneto rheological) in Audi car [1] [2] [8]

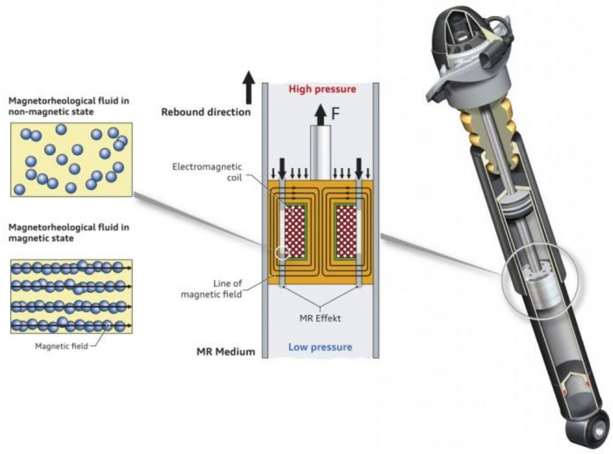


Fig 3(a) Magneto rheological damper [29]

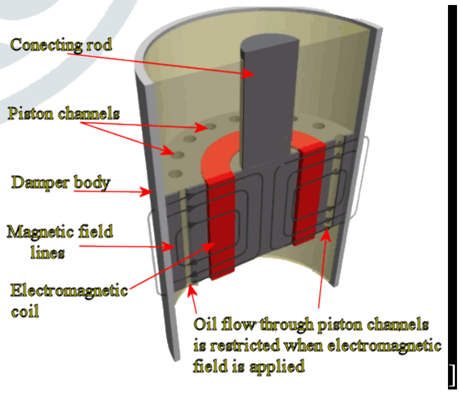


Fig 3(b) Magneto rheological damper [30]

Fig 3b in this damper with electric power, magneto rheological fluid is fluid with magnetic coagulant particles whose flow of magneto rheological fluid viscosity is control and damping level is controlled.[14] However, in semi- active system, no active force can be applied and therefore, total roll and pitch elimination is impossible. The semi-active suspensions are applied commercially to the Audi's car in Fig 3b and the quarter-car model of a typical semi-active suspension is depicted in little control of damping coefficient can be obtained in semi-active suspension.

Semiactive suspension system controls damping action and hence increases suspension performance. These controlled strategies may be, skyhook groundhook, hybrid, PID, Fuzzy Neural Network etc.[3]. Semiactive reduces compromise between ride comfort and handling but cannot completely eliminate; this can be achieved in active suspensio0n system.

Skyhook

The Skyhook law was patented in 1974 by Karnopp [7]. The damper connected to the sky (a fixed y-axis coordinate). An intuitive sense of how Skyhook control works, if the suspension damper is expanding and the sprung body is moving towards, then Skyhook control turns the damper on and the damper pulls down on the sprung body. The difference between Skyhook and passive is that the Skyhook controller varies the damper force such that the damper force is equal to,

$$F_{sa} = G_{sky}\dot{x}_s \; ; \; if \;\; \dot{x}_s V_{su} > 0$$
$$F_{sa} = 0 \; ; \; if \;\; \dot{x}_s V_{su} < 0 \qquad (3)$$

Where,

F_{sa} = Desired damping force, N

$\dot{x}_s$ = Sprung-mass velocity, m/s

V_{su} = $\dot{x}_s$ - $\dot{x}_u$; Relative velocity between sprung & unsprung-mass, m/s

G_{sky} = Skyhook gain, N/m/s

Ground hook control

The groundhook model differs from the skyhook model in that the damper is now connected to the unsprung-mass rather than the sprung-mass. Under the groundhook configuration, the focus shifts from the sprung-mass to the unsprung-mass. The logic of the groundhook control policy is similar to the skyhook control policy, except that it is intended to control the unsprung-mass.

$$F_{sa} = G_{gnd}\dot{x}_u \; ; \; if \;\; -\dot{x}_u V_{su} > 0$$
$$F_{sa} = 0 \; ; \; if \;\; -\dot{x}_u V_{su} < 0 \qquad (4)$$

Where,

$\dot{x}_u$ = Unsprung-mass velocity, m/s

G_{gnd}= Groundhook control gain, N/m/s

Hybrid control

An alternative semi-active control policy, known as hybrid control[4], combines the concept of skyhook and groundhook control to take advantage of the benefits of both. With hybrid control, the system can be set up to function as a skyhook or groundhook controlled system, or a combination of both.[22]

$$\sigma_{sky} = \dot{x}_s \; ; \; if \;\; \dot{x}_s V_{su} > 0 \quad ; \quad \sigma_{sky} = 0 \; ; \; if \;\; \dot{x}_u V_{su} < 0$$

$$F_{gnd} = \dot{x}_u \; ; \; if \;\; -\dot{x}_u V_{su} > 0 \; ; \; F_{gnd} = 0 \; ; \; if \;\; -\dot{x}_u V_{su} < 0$$

$$F_{sa} = G\,[\alpha\sigma_{sky} + (1-\alpha)\sigma_{gnd}] \qquad (5)$$

The variables σsky and σgnd are the skyhook and groundhook components of the damping force, α is the relative ratio between the skyhook and groundhook control also called as weighting factor, and G is a constant gain. When α = 1, hybrid control reduces to pure skyhook control, and when α = 0, it becomes groundhook control. As value of weighting factor tend from zero to one hybrid system changes from skyhook system to groundhook suspension system.

II.3 Active Suspension System

Full active suspension system refers to the energy that will be supplied into the system (Kruczek, A. and StribrskyJ 2004).[26] [28] [31]There are two types of configuration which are depending upon the link of passive part (spring and damper) and active part (controller).[6] [14] [18] [19] If these two parts are linked in parallel they are known as high-bandwidth configuration, meanwhile if those parts are linked in series, they are known as low-bandwidth configuration.[9] [15] [24]The advantages of high-bandwidth than low-bandwidth are to be able to control at the higher frequency and the suspension system will work continuously as a passive suspension in the event of an actuator is not working as an active part.[13] [25]

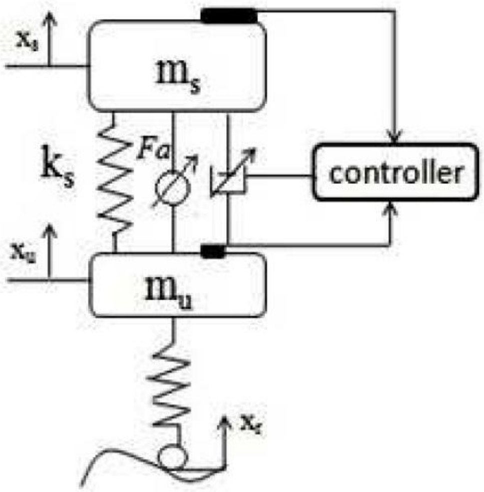


Fig 4 Quarter Car Active Suspension System

III. SUSPENSION SYSTEM MODELS
CLASSIFICATIONS

For dynamical performance with suspension system different models for car can be understand. There may different degrees of freedom with which car models can be classified such as quarter car, half car full car model.

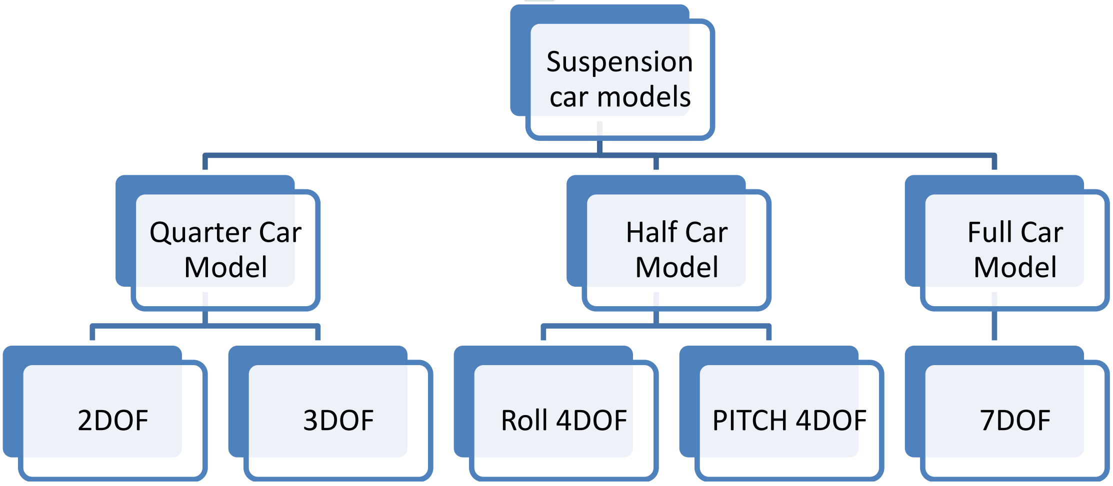


Fig 5. Classification of Suspension Models

On basis of types and working method classification of suspension can be mentioned as given below,

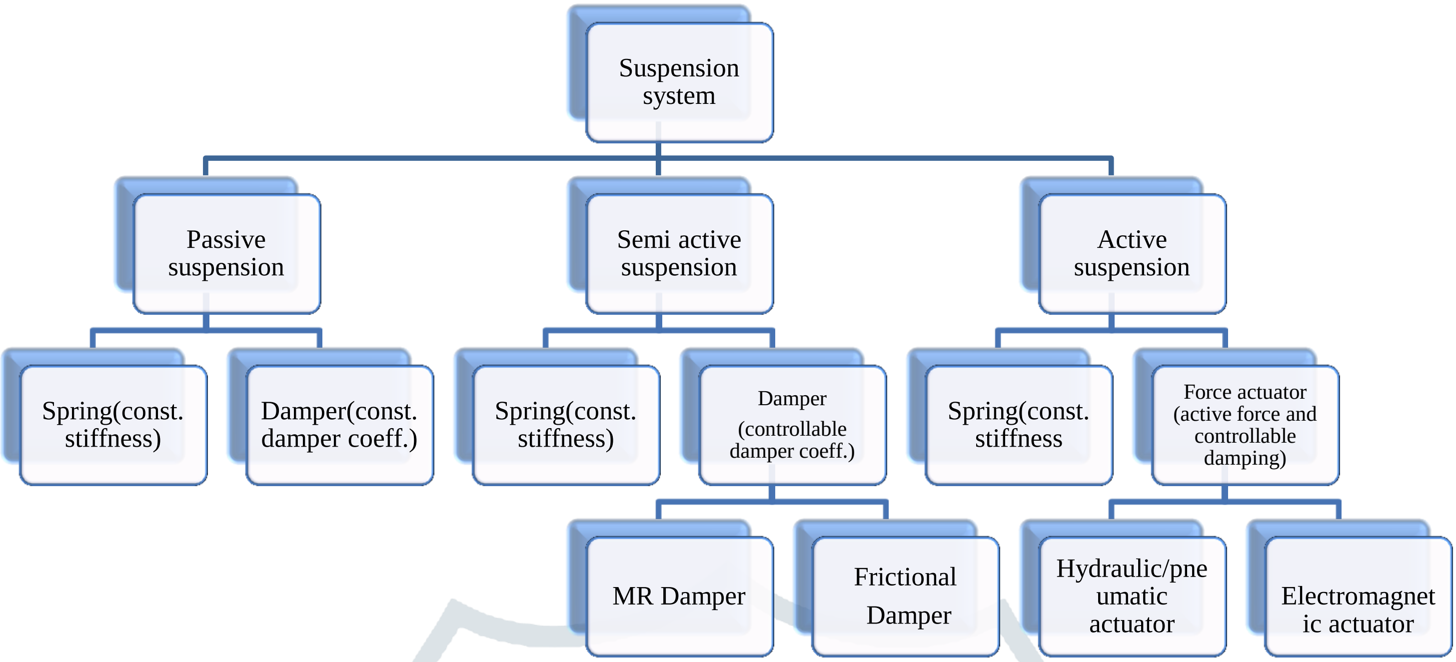


Fig 6. Classification of Suspension Systems

QUARTER CAR MODEL

With an independent suspension system vehical dynamics can be understood by considering one wheel suspension systems, quarter car model. An quarter car model can be considered with two degrees of freedom each at unsprung mass and sprung mass or one more degree considering passenger seat.

For quarter car sprung mass is considered to be one fourth of total vehicle mass.

Two-degrees-of-freedom quarter-car models, subjected to road excitation, are commonly employed in many areas of the automotive industry. These areas include the prediction of dynamic response, identification, optimization and control of ground vehicles. This is mostly due to the simplicity of the quarter-car models and the qualitatively correct information they provide, especially for ride and handling studies. Also, information extracted from such simple models provides quite frequently a firm basis for more exhaustive, accurate, and comprehensive studies with more involved dynamical car models (Verros et al., 2000a).[11] Governing Equation for two degree of freedom passive suspension system,

For *Sprung mass* m_s

QCM Sprung mass equation

$$m_s \ddot{x}_s + c_s (\dot{x}_s - \dot{x}_u) + k_s (x_s - x_u) = 0 \quad (1)$$

Unsprung mass m_u

QCM Unsprung mass equation

$$m_u \ddot{x}_u + c_s (\dot{x}_u - \dot{x}_s) + k_s (x_u - x_s) + c_t(\dot{x}_u - \dot{x}_r) + k_t (x_u - x_r) = 0 \quad (2)$$

Table 1: Parameters for QCM

Parameter	**Symbol**	**Unit**
Sprung mass	m_s	Kg
Unsprung mass	m_u	Kg
Damping coefficient	c_s	Ns/m
Tire damping	c_t	Ns/m
Spring stiffness	k_s	N/m
Tire stiffness	k_t	N/m
Critical damping ratio	ζ	-

Ride comfort has an impact at sprung masses while handling performance can be availed at unsprung masse. Acceleration at sprung mass determines ride and comfort performance. And displacement at unsprung mass relates vehicle handling.

III.1 HALF CAR MODEL

Half car model is considering either pitch or roll degree of freedom.[10] The half car model is one with sprung mass considered to be halved. In Roll degree of freedom when disturbance at left wheel of front axle is given then reaction on right wheel of front axle is considered, similarly in case of pitch degree of freedom. Pitch degree can be observed while passing through multiple speed breakers and roll degree can be observed while changing lane or at skill full maneuver. The half car model is used to investigate the dynamic response of cars with uncertainty under random road input excitations. The mass of the vehicle body, mass moment of inertia of the vehicle body, masses of the front / rear wheels, damping coefficient and spring stiffness of front / rear suspension, distance of the front / rear suspensions location to the centre of the gravity of the vehicle body and the stiffness of front / rear tires are considered as random variables.[12]

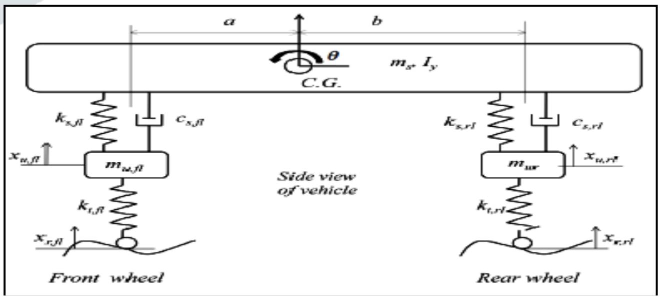


Fig 7. Half Car Suspension Model

There are two types of half car model viz, roll degree model and pitch degree of suspension system with each four degree of freedom. Two degrees of freedom at unsprung masses and two at sprung out of which one angular displacement is known as roll or pitch

III.2 FULL CAR MODEL

This model has been equipped with suspension force actuators to allow for the future development of an active suspension control system to improve the vehicle's ride comfort. These types of systems are becoming increasingly common on both passenger and commercial vehicles. The flexibility these systems offer allows them to be specifically tuned for performance or comfort, making them optimum for many applications. [11]

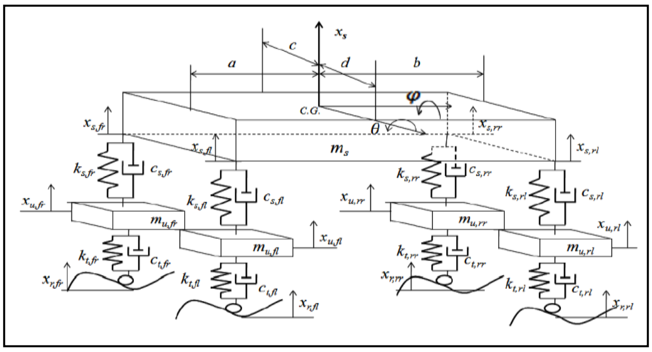


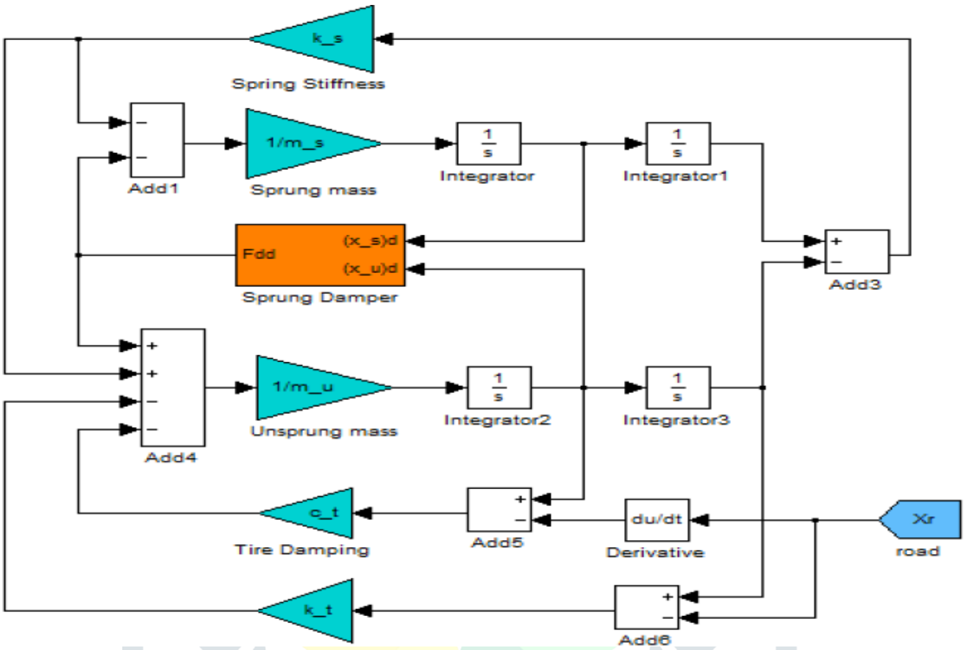
Fig 8. Full Car Suspension Model

IV. SIMULATION OF QUARTER CAR MODEL

Quarter car model can be simulated in different simulation software's such as Matlab/SIMULINK to understand dynamics of vehicle. Simulation model with governing equations of motion for the sprung and unsprung masses of the passive quarter car model can be prepared. For advanced suspension changes at damping control or external actuator can reduce compromise in ride comfort and handling.

Assumptions of a quarter car modeling are as follows: the tire is modeled as a linear spring without damping, there is no rotational motion in wheel and body, the behavior of spring and damper are linear, the tire is always in contact with the road surface and effect of friction is neglected so that the residual structural damping is not considered into vehicle modeling.

For higher degrees of freedom, half car and full car suspension system, model size multiplies wit complexity, and parametric blocks.



CONCLUSION

From grand literature some conclusions can be made on basis of some parameters and their distinguishing importance.

Design of adequate suspension system is a highly a difficult control problem due to the complicated relationship between its components and parameters. The researches were carried out in suspensions systems cover a broad range of design issues and challenges. As degrees of freedom goes on increasing from one degree (whole system) to four, seven, eight etc. complexity in analysis increases. While two-degree of freedom suspension system can give effective Performance measurement with less complexity and simple structure.

The present studies of electromagnetic active suspensions handle with permanent-magnet linear actuators.

As per different parameter such as Structure weight /volume, Cost economic balance, performance on basis of ride comfort and handling,. Reliability, Dynamic Performance, whether it can generate energy and can be commercialize.

	Skyhook	**Groundhook**	**Hybrid**	**Fuzzy**	**PID**	**Neural Network**	**Structure Weight/Volume**	**Dynamic Performance**	**Commercial maturity**
Passive suspensions	Compromise in Ride and Comfort	Compromise in Ride and Comfort	Compromise in Ride and Comfort	Compromise in Ride and Comfort	Compromise in Ride and Comfort	Compromise in Ride and Comfort	Simple		
Semi-active suspensions	Good Ride & Comfort	Good Handling	High	Very High			Medium		
Hydraulic/ pneumatic active suspensions	Good Ride & Comfort	Good Handling	Very High	High			Complex & High infinitesimal wt		
Electromagnetic active suspensions	Good Ride & Comfort	Good Handling	Good	Very Good					
Research work available thru literature									

Quarter Car	More	Medium	Medium	Less	Less	Less			
Half Car – Roll	Less	Less	Less	Less	Less				
Half Car – Pitch	Less	Less	Less	Less	Less				
Full Car	Very Less	Very Less	Very Less	Very Less	Very Less	Very Less			

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