

Review on Study of Magneto-Rheological Damper for Vehicle Suspension to Compare its Outcome with Passive Suspension

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Abstract- Magnetorheological (MR) fluid is a smart material as it's flow characteristics can be altered and controlled easily in the presence of the magnetic field. The MR fluid tends to convert from liquid state to semi solid-state when the magnetic field is applied and that is why it is used in MR technology-based Dampers, brakes, clutches, and bulletproof jackets, optics and aerospace industry and many more. In this review paper, we have focused on MR based shock absorber for the use in Automobiles. We have studied the working of MR dampers and its mechanical advantage. We reviewed the performance results between Passive and semi-active suspension based on the simulations performed by various authors. For control methods we have considered PID, Skyhook and Fuzzy logic control method to support the simulation. Finally concluded that Results proved out that semi-active suspension system has much better performance than passive one in terms of both Ride and Handling ability of the vehicle.

Key Words- Magnetorheological damper; Passive damper; Semi-active suspension; Magnetorheological fluid; Active suspension, Magnetic suspension

1. INTRODUCTION

Automobile sector is one of the major industry in across the world. It is continuously improving. One of the area going under improvement is the Suspension system. The primary function of the cars suspension system is to provide a smooth ride by isolating the vehicle from bumps, vibrations and road noises. Undesired vibrations and forces are concern for engineers and developers and hence they are always trying to make better energy dissipating dampers. There is need for real-time performance adjustment capability on the dampers based on road profile.

There are three types of suspension system classified as Passive, Semi-active and Active type Suspension explained by [1] The most of the automobile dampers equipped on vehicle we see today is a type of passive dampers. Passive suspension typically includes a spring coil and a damper of fixed stiffness. These dampers offer decent performance but have limited performance range is observed.

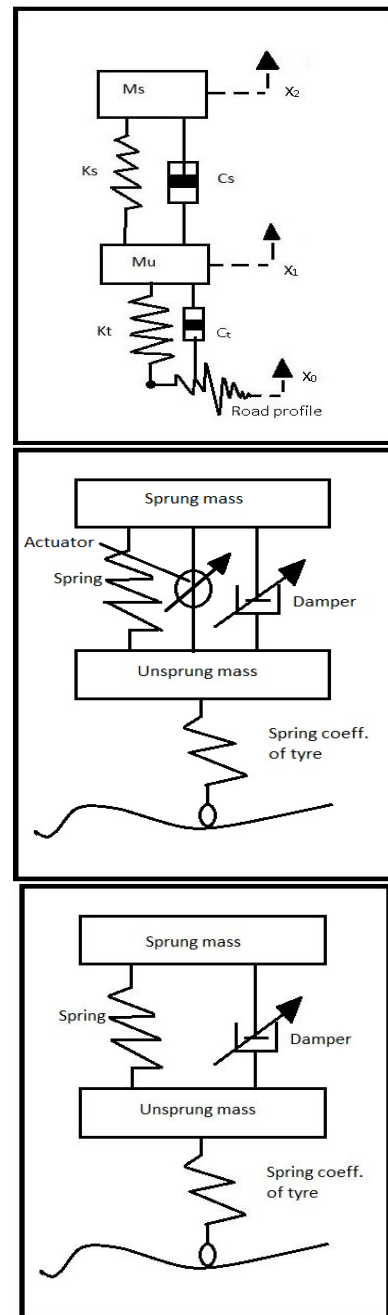


Fig 1: Suspension model of

(a) passive (b)semi-active (c) active

This is now being advanced by semi-active suspension, that have variable damping coefficient of the damper. The semi-active suspension has a built configuration similar to conventional shock absorber except that the hydraulic oil is replaced with a Magnetorheological fluid and an introduction of conductor coil assembly in the piston.

It has quick response (within few milliseconds) and offers range of damping values. It does not add energy to the system. It consumes less energy and cost effective in comparison with Fully active suspension.

The most advance is the fully active suspension spring coil, actuator and damper of variable coefficient. The actuator controls the vertical motion by raising or lowering the chassis. It adds energy to the system hence called active system. It works on closed feedback loop. Overall it offers superior level of ride and handling quality. Since each wheels can be controlled independently, it offers body roll and pitching control over various dynamic conditions.

2. MAGNETORHEOLOGICAL FLUID PROPERTY AND BEHAVIOUR

The Magneto-Rheological(MR) fluid is a Smart fluid that responds to magnetic fields. They can change their physical state from the Newtonian fluid to the semisolid state within a few milliseconds when a magnetic field passes through it. These fluids are composed of three components are Magnetic particles, carrier fluid, and surfactants[2]. In general, the MR fluid is composed of around 20 to 40 percent magnetic particles inside of it. Soft iron is mostly preferred as its metal particles provide good yield strength and are economical. For carrier fluid, synthetic oil, mineral oil, and glycol-based oil are preferred. A good carrier fluid will make a good colloidal solution with magnetic particles. Finally, for surfactants, oleic acid, tetramethylammonium hydroxide, citric acid, soy lecithin is used. They help to avoid settling of heavier particles in mixture by initiating micelle formation. Moreover, they also provide lubrication, modify viscosity and reduce wear.

When the fluid is kept between two poles and the magnetic field lines induced perpendicular to the flow of fluid, the magnetic particles acquire a magnetic bipolar and redesign themselves in a chain-like structure in the direction parallel to the flow of magnetic field lines and offers resistance to flow. The higher the intensity of magnetic field, the higher the resistance to flow.

The behaviour of MR fluid is similar to Bingham Plastic following Bingham law.[3] The stress point at which no shear rate is there is called Yield stress. The MR fluid has zero shear rate below yield stress and behaves like a solid material, while above yield stress, the shear stress possesses linear relation with shear rate and fluid flow viciously. The yield stress will be proportional to the amount of magnetic field applied to the fluid. Typical MR fluid can have maximum

yield stress of 50-100 kPa. They require less electric power for operation and hence they can be easily powered via existing car battery power.

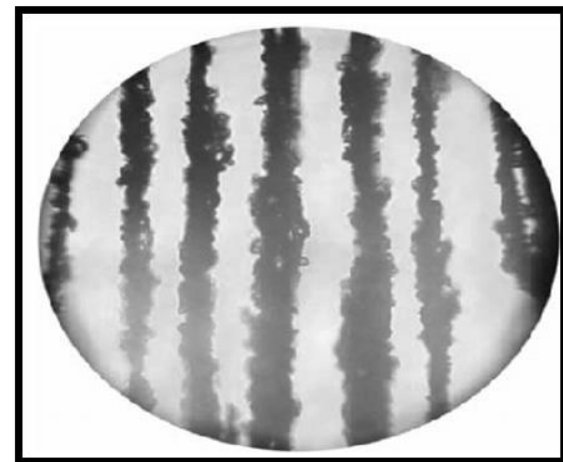
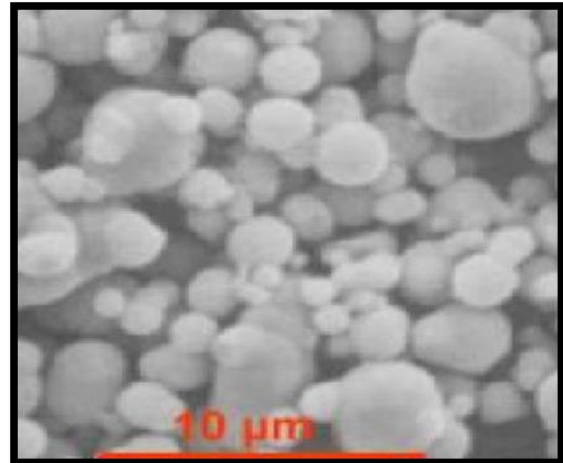


Fig 2: (a) Microphotography of MR fluid when the magnetic field is absent (when particles are randomly dispersed). (b) Microphotography of MR fluid when the magnetic field is present (when parallel chains of magnetic particles).

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LORD corporation is one of the leading manufacturer of MR fluids. The properties of some of the MR fluid products are given below.

Properties	MRF-122EG	MRF-132DG	MRF-140CG
Base	Hydrocarbon	Hydrocarbon	Hydrocarbon
Appearance	Dark Grey Liquid	Dark Grey Liquid	Dark Grey Liquid
Viscosity, Pa-s @ 40°C (104°F)	0.042 ± 0.020	0.112 ± 0.02	0.280 ± 0.070
Density g/cm ³	2.28-2.48	2.95-3.15	3.54-3.74
Solids Content by Weight, %	72	80.98	85.44
Flash Point, °C	>150	>150	>150
Operating Temperature, °C	-40 to +130	-40 to +130	-40 to +130

Fig 3: Lord MR fluid properties

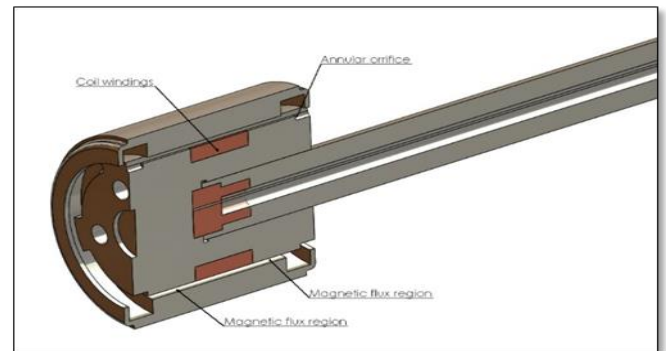


Fig 4: a) A typical MR damper and b) piston assembly

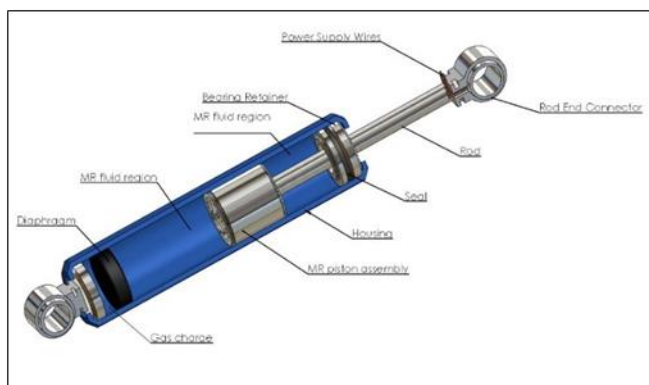
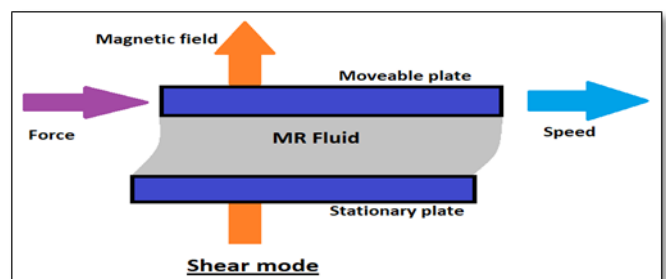
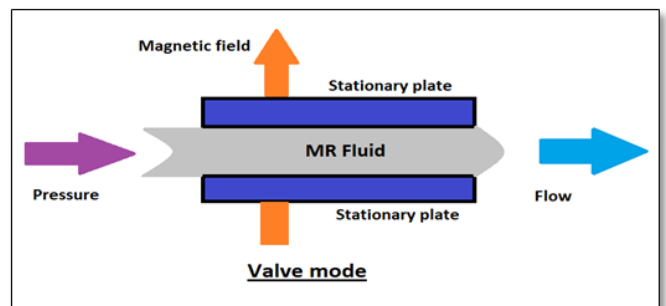
Due to its unique property it is being used in various domains including Mechanical engineering, Military and defence, optics, Automotive, Aerospace and Human prosthetics. [4]. By suitably selecting different modes of operation, we can increase the number of application use. The application of MR fluid has a vast opportunity and with each advancement, it will expand.

3. MAGNETORHEOLOGICAL DAMPERS

MR damper uses MR fluid in place of hydraulic oil. An Electromagnet coil is introduced in the piston assemble which controls the flow of MRF in the orifice. When suitable electric current is supplied, it induces magnetic field in the piston orifice that offers resistance to MR fluid flow as it increases its viscosity. The intensity of magnetic field is controlled by the control unit comprising of a microprocessor which gets various information from various sensors located all over the vehicle that tells about road bumps and driving conditions. The control unit then regulates the electrical current supplied to the dampers and ultimately controlling its damping coefficient.

This technology was initially developed by General Motors in cooperation with Delphi Corporation. It was first launched in 2002 on the Cadillac Seville luxury car. These systems are now available for OEMs in several vehicles like -Audi (R8 & TT), Acura MDX, Cadillac (CTS-V, DTS, XLR, SRX, STS), Buick Lucerne, Chevrolet Corvette, Ferrari (599GTB, 458 Italia, F12), and Berlinetta.

There are three modes of operation provided to control the MR damper. They are Valve mode, Shear mode and squeeze mode.[5] In valve mode; we can control the flow resistance between two stationary poles by applying the required magnetic field in the perpendicular direction of flow. Examples include actuators, servo valves, and MR dampers shock absorbers. In shear mode, MR fluid is flowing between a pair of two moving poles that move parallel to each other. We can also control drag force and apparent viscosity created by fluid by applying a magnetic field between the poles. The application includes clutches, brakes, locking devices, etc. In squeeze mode, by changing the distance between the pair of two parallel poles, we can get squeeze flow. In general, high forces are achieved in this squeeze mode with relatively low displacement. Its application in vibrational control and impact dampers.



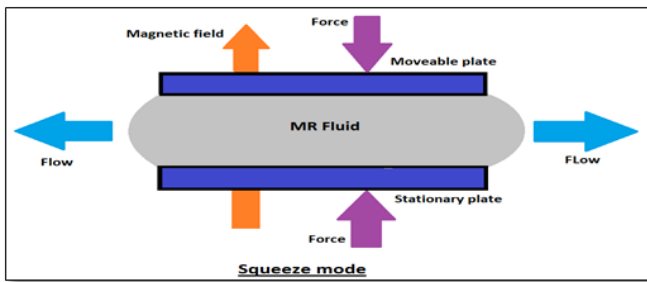


Fig 5: Various modes of operations of MR fluid- 1)Valve mode 2) Shear mode 3) Squeeze mode

We can classify MR damper variation into three main categories, the monotube, the twin-tube, and the double-ended MR damper[6]. The monotube dampers consists single cylinder which is separated into two sections by piston valve assembly. The monotube shock absorber has a greater inside cylinder dimension compared to the twin one. This offers more volume for damper fluid and a larger piston, which creates a wider area of pressure. Additionally, it improves the heat dissipation capability of the shock absorber. Next, is the Twin type MR damper and its construction is similar to hydraulic telescopic type. MR Twin shock absorbers have two cylinders- one inner cylinder (working chamber) and the other with an outer cylinder (reserve chamber) that are in concentric with each other. The third one is the Double ended MR damper. Two dynamic seals or piston heads are presently connected to the main rod. The piston rod of equal diameter extends from both ends of damper housing. The volume held inside between two seals remains unchanged and eliminates the need for an accumulator. When one of the pistons is compressed, the MR fluid moves to the next reservoir through a control valve. Control valve induced magnetic field resists the flow and thus we can control the damper. It's being used in bicycle dampers, gun recoil, etc.

4. QUARTER CAR MODEL

The quarter car model is preferred for analysis of simulation of Semi-active suspension model of an automobile to look into the vibration response of vehicle suspension system against road excitations. Hence, its applied to both passive and semi active for making comparison experiment. Quarter portion considers a quarter portion of a vehicle for analysis. This helps in simplification of the calculation being involved.[7] We can divide the model into three sections: Sprung and Unsprung mass and Road surface. We can then measure the relative displacement and its rate of change between sprung mass, unsprung mass and road surface. This will provide a gateway for making input feed for the mathematical model and control system.

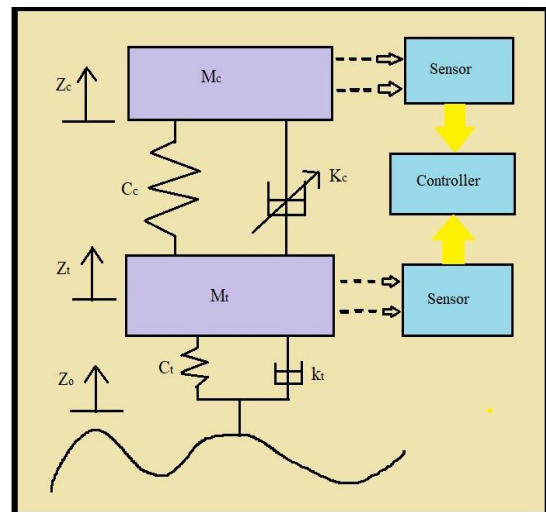


Fig 6: 2 DOF Quarter car model of Semi-active suspension

5. Mathematical Equation of Motion

We apply Newton's second law to get expression:

- I. For Sprung mass:

$$M_c \ddot{Z}_c + K_c (\dot{Z}_c - \dot{Z}_t) + C_c (Z_c - Z_t) + F_{MR} = 0 \text{ ----1}$$
- II. For Unsprung mass:

$$M_t \ddot{Z}_t - K_c (\dot{Z}_c - \dot{Z}_t) - C_c (Z_c - Z_t) + C_t (Z_t - Z_0) = F_{MR} \text{ ---2}$$

Where, $M_c =$ sprung mass , $M_t =$ unsprung mass,
 $Z_c =$ sprung mass displacement
 $Z_t =$ unsprung mass displacement ,
 $Z_0 =$ road displacement
 $C_c =$ spring stiffness , $C_t =$ tyre stiffness ,
 $K_c =$ damping coefficient
 F_{MR} is the controllable damping force.

We can create variables for them;

$$\begin{aligned} x_1(t) &= Z_c(t) - Z_t(t) \\ x_2(t) &= Z_t(t) - Z_0(t) \\ x_3(t) &= \dot{Z}_c(t) \\ x_4(t) &= \dot{Z}_t(t) \end{aligned}$$

We can rewrite equation 1 as;

$$M_c \dot{x}_3(t) + K_c (x_3(t) - x_4(t)) + C_c (x_1(t)) + F_{MR} = 0 \text{ ----3}$$

Equation 2 can be:

$$M_t \dot{x}_4(t) - K_c (x_3(t) - x_4(t)) - C_c (x_1(t)) + C_t (x_2(t)) = F_{MR} \text{ ----4}$$

Therefore,

$$\begin{aligned} \dot{x}_1(t) &= x_3(t) - x_4(t) \\ \dot{x}_2(t) &= x_4(t) - \dot{Z}_0(t) \\ \dot{x}_3(t) &= -\frac{F_{MR}}{M_c} - \frac{C_c(x_1(t))}{M_c} - \frac{K_c(x_2(t))}{M_c} + \frac{K_c(x_4(t))}{M_c} \\ \dot{x}_4(t) &= \frac{F_{MR}}{M_t} - \frac{C_t(x_2(t))}{M_t} + \frac{C_c(x_1(t))}{M_t} + \frac{K_c(x_3(t) - x_4(t))}{M_t} \end{aligned}$$

The equation can be written as;

$$\dot{x}(t) = Ax(t) + BU(t)$$

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{Bmatrix} = \begin{Bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{C_c}{M_c} & -\frac{C_c}{M_c} & -\frac{K_c}{M_c} & \frac{K_c}{M_c} \\ \frac{C_t}{M_t} & -\frac{C_t}{M_t} & \frac{K_c}{M_t} & -\frac{K_c}{M_t} \end{Bmatrix} \cdot \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{Bmatrix} + \begin{Bmatrix} 0 \\ 0 \\ -\frac{1}{M_c} \\ \frac{1}{M_t} \end{Bmatrix} \cdot F_{MR} + \begin{Bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{Bmatrix} \cdot \dot{z}_o$$

These equations are then solved using MATLAB SIMULINK.

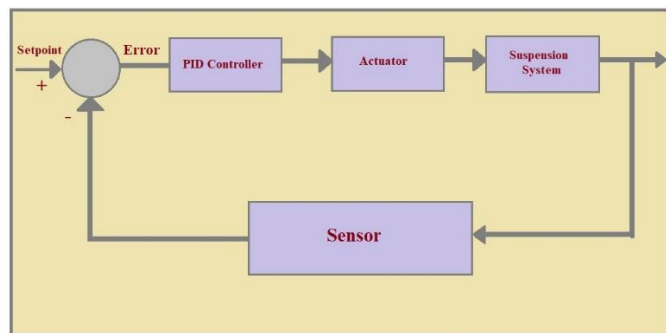
6. CONTROL METHODS

Control Methods provides unique controlling algorithm to control the working of an MR damper. There are various types of control methods used. We will discuss about PID, Skyhook and Fuzzy logic based control methods to control the semi active suspension.

6.1 PID CONTROL METHOD

PID is an acronym and its stand for Proportional Integral Derivative.

PID control methodology is being used most widely and provides reliable results. This control logic is based on the closed-loop system. The system runs on continuous closed-loop and process is repeated until the output is reached to set-point.



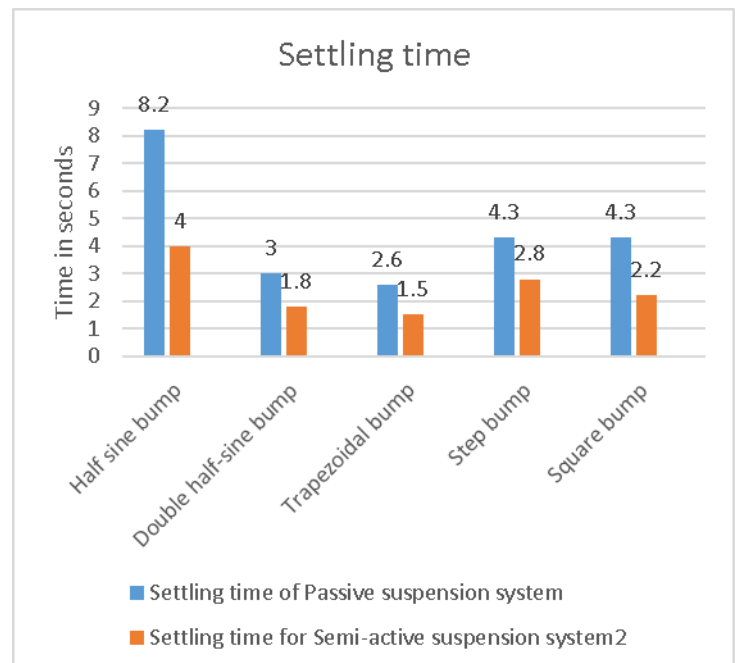
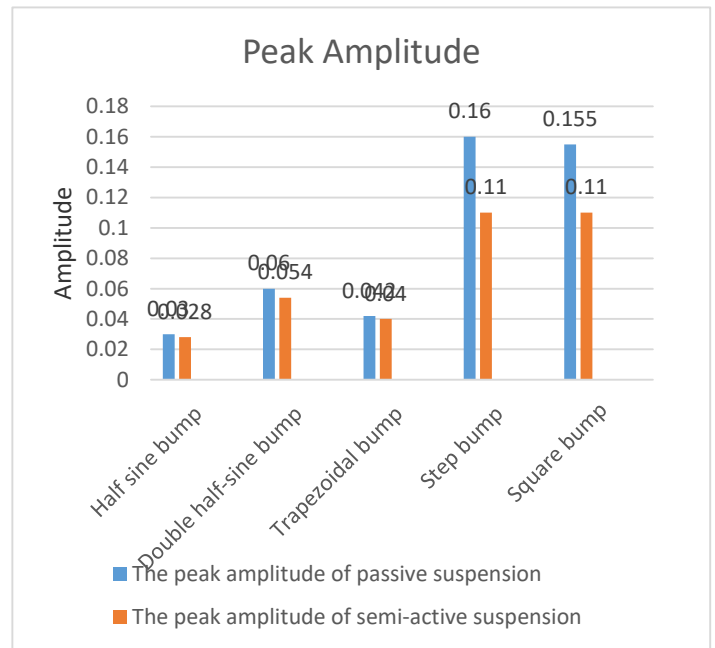
Suspension system using PID controller

Fig 7: Block diagram of PID controller

The author [8] tested simulations with various vehicle velocity, bump profile and certain bump height. The input parameters were taken of a quarter car model for the equations. The sprung mass displacement with different velocity was observed. It was observed that velocity change results in a change in peak amplitude and settling time. The shorter the settling time, the better will be the performance of the damper. The authors performed an experiment in which vehicle velocity was taken as 40kmph with bump height of 0.1m and tested its result in MATLAB SIMULINK for

different road profiles. The test results were presented in the Graph 1.

Graph 1- Settling time Improvement percentage(%),Adopted from ref.8, Comparison of passive and semi-active suspension system by MATLAB SIMULINK for different road profiles



Results show that the PID controlled in Semi-active suspension proved to provide improved performance than the passive suspension system. PID can be designed and tuned to provide good ride comfort, handling and reduced settling time.

Another study conducted by [9] implemented self-tuning PID controller on a quarter car model. Also passive suspension and suspension using P, PI, PD, and PID control method were compared for performance. Mathematical model of Quarter car model is implemented on Matlab Simulink and general parameters were taken for input.

The experimented was performed on three types of road profile; first one having single bump of 0.1 m and 0.1 Hz sinusoidal type ; second one with single 0.1 m step bump and 0Hz frequency ; and last one with three simultaneous bumps of different amplitude with 0.1 Hz frequency. The outcome was compared on basis of linear displacement of suspension and settling time of damper. The author found that suspension with PID method outperformed passive suspension with P, PI and PD based on various parameters like settling time, rise time, overshoot percentage and number of oscillations.

[10] also presented experiment similar to Phalke, 2016. The value of K_p, K_i and K_d were found out by Hit and trial method .The step type and random type bump profile were taken into consideration. In results , it showed that the peak overshoot vehicle body acceleration, vehicle body position, vehicle suspension Deflection, vehicle body wheel position and vehicle wheel deflection is significantly less PID based suspension. This will increase comfort level and stability of vehicle.

6.2 SKYHOOK CONTROL

Skyhook principle works like a vehicle is hung from an imaginary hook in the sky, maintaining a stable posture and unaffected by road conditions. An imaginary damper can be assumed between sprung mass and sky. This method requires two sensors namely sprung mass acceleration and relative displacement sensor.

[11] implemented ON-OFF skyhook control method as it simpler and Industrial suitability. The logical strategy is like when the relative velocity between sprung and unsprung mass is in the same direction then maximum damping force must be introduced to control body acceleration. On the other hand if the relative velocity is in opposite direction, then damping force should be minimum.

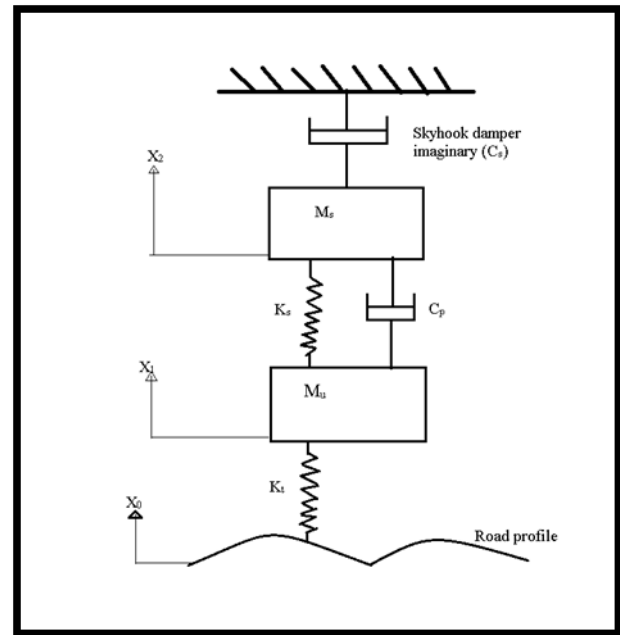


Fig 8 : A typical skyhook physical model is shown below

Abbreviations:

X_0 : Road surface displacement,

X_1 : Unsprung mass displacement,

X_2 : Sprung mass displacement,

M_s : Sprung mass ,

M_u : Unsprung mass,

C_s : Skyhook damping coefficient,

C_p : Passive damper coefficient,

K_s : Suspension spring constant, K_t : Tire stiffness

The author implemented this model on Matlab Simulink. Again a quarter car model is used for simulation purpose. Certain considerations like Road bump of 100 mm with sinusoidal type, vehicle speed of 40 kmph and 10 second response scale were taken.

Results shows there was 51.13 % increased settling time of sprung mass in passive suspension as compared with semi-active one. While the unsprung mass settling time was 53.33% more in passive suspension as compared with skyhook controlled semi-active suspension.

Table 2: Peak to peak Displacement of sprung and unsprung mass

Input	Displacement	Passive	Skyhook
Sinusoidal input (bump)	Max. sprung mass displacement(mm)	82.12	64.56
	Max. unsprung mass displacement (mm)	92.45	92.45

From the simulations results, we can say that skyhook control can significant achieve reduction in peak displacement and settling time.

[12] compared the results of suspension with Passive type in which Skyhook control and Minimax strategy using SILS and results were presented. For this, 2 Dof quarter car mathematical model were implemented in Matlab Simulink with On-Off Skyhook control method. When sprung and unsprung mass relative velocity is in same direction, then maximum damping force is applied. On contrast, if they are in opposite direction, then minimum damping force should be applied. In contrast, the Minimax control strategy works by taking input of the damper velocity and wheel load condition, and thereby switching the damper between hard and soft lining by controlling the damper supply current (0 for soft and 0.6 Amp for hard). Finally, for experimentation, sine wave bump profile with 1 cm amplitude were taken. From results, it was found that skyhook control method was effective in decreasing vertical body acceleration effectively and improving ride comfort. On the other hand, Minimax strategy was useful in improving safety of wheels by controlling wheel loadings.

Skyhook control system generally employ two sensors; one to measure sprung mass acceleration and other to measure relative displacement. These measurement signals are then converted into corresponding velocities and then these velocities are used to decide the desired damping level. Finally, the damping control signal passed on to controllable damper to reduce vibration. [13] proposes a new simplified skyhook control by eliminating one sensor to reduce cost and complexity. This paper demonstrated cost effectiveness by using one effective accelerometer sensor. Using to quarter car model, the idea is explained by analysis of phase relationship between two velocities that are essential for skyhook control. Then estimating the relative velocity by sprung mass acceleration is formulated. An effective control system is demonstrated by a simulation study of a car suspension system with MR damper.

[14] discuss the development, modelling and testing of skyhook and minimax control strategies for semi active suspension. The performance of this is strategies was investigated using Matlab Simulink with two degree of freedom quarter car model. The comparison were made by using software in loop simulation (SILS) method and this

paper also discuss the outline for the development of hardware-in-the-loop (HILS) method. The results found after the simulation shows that skyhook reduces the resonant peak of body and provide greater vehicle ride comfort whereas minimax strategy can be used to get better drive safety of the vehicle by influencing wheel load. This paper also suggest that both the strategies can be used and switched to get good of both the strategies.

[15] aim to analyze the effect of Skyhook and Groundhook strategies on a semi-active suspension system. Computer simulation of quarter car model through Matlab Simulink. This paper focuses on the parameter Road profile for finding which one of these two is better by creating a mathematical model. The outcome of this research paper is that Groundhook system offers better ride comfort and handling as compared to skyhook and passive suspension. Also, this paper discusses other important factors such as time domain, frequency domain, power spectral density, and root mean square values to get better control out from SkyHook and Groundhook strategies.

6.3 Fuzzy Control system

A fuzzy control system is based on fuzzy logic – a mathematical system that takes analog input value which is continuous between 0 to 1, unlike digital discrete value - either 1 or 0. We do not need much detailed knowledge of the system. The controller action is determined by the Linguistic rules. Fuzzy logic can replace human intelligent in decision making process. They can handle more variability in the inputs hence it is robust.

[16] proposed a model in Matlab Simulink consisting of quarter car model, road profile, MR damper model based on Bouc-wen and the Fuzzy logic controller model were embedded to track the desired damping force.

The author used two controllers in semi-active suspension model- system controller and damper controller. System controller utilizes fuzzy logic to control desired damping force.

While Damper controller controls the voltage supplied to the current driver. It evaluates how much current needs to be supplied to driver board by tracking desired and actual damping in the system.

Table 3: Body displacement and suspension deflection comparison table

Suspension type	Body displacement(mm)	Suspension deflection(mm)
Passive	524	218
Semi-active	465	144

The results showed that there is approximate 10% improvement in ride comfort and 30% improvement in vehicle stability.

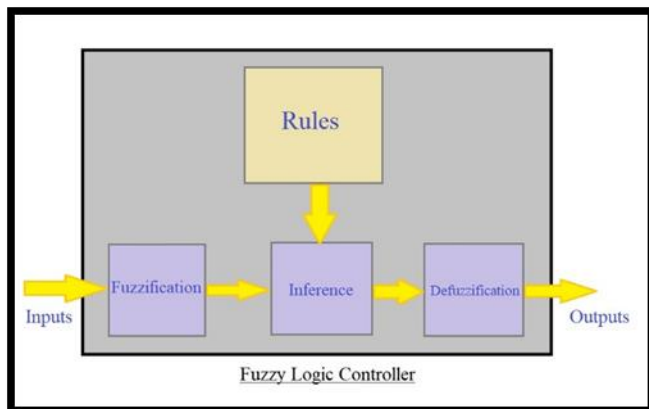


Fig 9: Block diagram of fuzzy logic controller

[17] made a comparison using five different types of control strategy including skyhook, hybrid, the LOQ, sliding mode controller and fuzzy logic based on quarter car model. For physical testing, the four MR dampers were installed on a mini passenger car. The vehicle was test-run through random road profile with test speed of (40, 60, and 80 kmph). The results showed that all these control methods were more successful than alone passive suspension. He found out that, fuzzy logic controller has better ride comfort than LQG and hybrid controller but was lagging behind skyhook and sliding mode controller. Sliding mode control algorithm outperformed from the remaining control strategy.

[18] implemented the quarter car model and compared Semi active MR and passive damper using Matlab Fuzzy logic control toolbox. For input of fuzzy logic, the difference between response value and expected value of body vertical acceleration and the rate change of acceleration are considered.

The adjustable damping force is taken as output. The seven different linguistic variables were taken for input and output. The result was ofcourse superior to passive one. Author suggested to combine use it with other control methods like PID control, will give even better results. We can further apply for 7 Dof full vehicle suspension model to get complete expected vehicle and suspension performance data.

7. CONCLUSION

This paper overviews on MR damper and control methods to draw comparison between the passive and semi-active suspension. Common control methods include PID, Skyhook and Fuzzy logic controller were studied and results were noted down. The result concluded that semi-active suspension provides better handling and rides quality than the passive suspension. Furthermore, it is less complex than full active suspension and provide good price to performance ratio.

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