Modeling and Simulation of a Semi-active Vehicle Suspension system using PID Controller

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Abstract. In this article, the numerical simulation of Magneto-rheological (MR) damper has been done using PID controller in Matlab-Simulink software to compare between the regular Macpherson strut and semi active suspension systems. The Magneto-rheological damper is a control device filled with Magneto-rheological fluid which changes damping force by changing property of viscosity on application of magnetic field. The results show that proportional integral derivative (PID) controller used to control damper in semi-active suspension is more efficient to reduce road disturbances than the regular suspension using Macpherson strut. Vehicle chassis displacement and acceleration can be reduced within milliseconds of time.

Keywords. Magneto-rheological (MR) Fluid, Sedimentation, Viscosity, Semi-active Suspension, Sprung mass

Nomenclature
m1 = Sprung mass, Kg
m2 = Unsprung mass, N/m
k1 = Suspension stiffness, N/m
k2 = Tire stiffness, N/m
c1 = Damping coefficient of suspension, Ns/m
c2 = Damping coefficient of Tire, Ns/m
x1 = Displacement of the sprung mass, m
x2 = Displacement of the unsprung mass, m
w = Road disturbance, m
ξ = Damping factor
ωn = Natural frequency of system, rad/s
ω = Forcing frequency of unsprung mass

1. Introduction

Suspension system along with tire is an important area of concern in a vehicle, which affects ride quality of a passenger car. A superior ride quality provides a comfort to passengers sitting in the vehicle. Speed bumps, pot holes and irregular road profile are main cause of vibrations in automobile. Roughness of road, rotating components coupled to the tire and engine creates vibrations during the ride of vehicle. Many researchers revealed that vibrations affect the human health and cause loss of working efficiency. Suspension system prevents these shocks and vibrations and provides comfort to the passengers. Along with comfort suspension system also carries the total load of the vehicle.

Damper is the most important element of the suspension assembly to ensure ride comfort and good control over the car by dissipating vibration energy. The automotive damper on most suspension
systems are hydraulic and operate on the dashpot principle. Any relative motion between the axle and the car body results in a piston moving in a cylinder filled with oil. Considerable amount of viscous force oppose the relative motion across the car body, and this damping force is directly proportional to the velocity of vibrations. The most desirable amount of damping in these shock absorbers depends on the road condition. When running over a smooth road with rolling hills and valleys, critical damping is needed. On the other hand, if the road has short quick bumps, a small damping is desirable (J. P. Den Hartog, 1956[1]). However, it is appeared that the variability in the types of road unevenness is too great for changing the damping constant of passive damper. Adaptive suspension, Semi-active and active suspension can eliminate the drawback of regular suspension. To improve the ride quality and stability of vehicle, adaptive suspension can be used where it has a regular spring and adjustable damper with slow response. To increase the response time in milliseconds and control the damping force in real time, a semi-active suspension is used. Active suspension is a feedback controlled system that isolates the wheel from chassis of the vehicle body and effect of road roughness is not transferred to the passengers but at high cost. Semi-active suspension can also serve the purpose at low cost and can show reasonable performance as compared to that of an active suspension system. The rheological effect of controllable fluids, such as magnetorheological fluid or electro-rheological fluid is used in Semi-active system. Magneto-rheological (MR) fluids are rheological materials with magnetic particles mixed in carrier fluid along with additives or surfactants. Due to their variable rheological behaviour, Magneto-rheological fluids have bright future for applications in brakes, engine mounts and shock absorbers (Kciuk M. et al., 2009[3]).

2. Literature Review

To isolate the car body from disturbances of road, authors have studied on variable stiffness and variable damping methods. Yanqing Liu et al. have used two controllable dampers and springs, however controlling of spring is complicated to implement (Yanqing Liu et al. 2007[2]). Hence authors have tried changing damping force with element like magnetorheological damper. MR Damper is similar to regular hydraulic damper filled with fluid that moves between different chambers through small holes in the piston, with additional feature of an electrical coil around the piston which creates a magnetic field and changes the viscosity of oil. This change in viscosity is rapid and can come to original value within short period of time. By applying magnetic field in magnetorheological damper state of fluid can be changed from free flowing fluid to thick fluid like grease and vice versa. This concept can be used in different applications like suspension, MR Brake where braking torque is applied with the help of solid fluid and in magnetic bearings (Goncalves F. D et al., 2006[4]). High cost of MR fluids ( US$ $816 per liter) and sedimentation problem is the major drawback of MR fluid (Sukhwani V. K and Hirani H, 2006[5]). Sedimentation problem can be solved by adding soluble surfactants or by using nano particles with magnetic properties and by coating particles with green additives .Nano particles or nano magnetized particles can improve sedimentation and stability but it also reduces the magnetic effect of the fluid (Bhau K. Kumbhar et al., 2015[6]). Strong nonlinear dynamical behaviour is exhibited by the magnetorheological damper which is a key challenge while solving equations. To characterize the dynamic behaviour of MR dampers, Bingham model, the classic Bouc-Wen model (Spencer et al., 1997[7]) and the modified Bingham hysteresis model (Yang et al., 2005[8]) are studied by the authors.

3. Analytical Modeling of a Quarter-Car Model

Two degree of freedom quarter car model is used to design a Suspension system. Figure 1 shows a chassis and vehicle body mass $m_1$ also known as sprung mass and mass $m_2$ known as unsprung mass which take account of suspension and tire. To generate equations of motion and solve numerical simulations for vibration isolation performance, free body diagram of one of the four wheels (Quarter car model) is presented.
Vehicle comfort and ride quality depends on the acceleration of vibration transferred by the sprung mass to the end user. Lower the acceleration, better is the comfort and with high acceleration vibration increases. The equation developed from Newton’s second law for acceleration of sprung mass is given as follows

\[ \ddot{x}_1 = \omega^2 \cdot \sum_{i=1}^{\infty} \frac{1+(2\xi i)^2}{(1-r)^2+(2\xi i)^2} \]  

(1)

Where \( \xi \) is damping factor, \( \omega_n \) is the natural frequency of system, \( \omega \) is the forcing frequency of unsprung mass excitation, \( k_1 \) is the sprung mass stiffness, \( k_2 \) is stiffness of tire, \( r \) is the frequency ratio (\( \omega / \omega_n \)). From equation 1 it is observed that the mass of vehicle and forcing frequency affects the acceleration of vibration. The equations of motion for the vibratory system modeled are given as

\[ m_1 \ddot{x}_1 + c_1 (\dot{x}_1 - \dot{x}_2) + k_1 (x_1 - x_2) = 0 \]  

(2)

\[ m_2 \ddot{x}_2 - c_1 (\dot{x}_1 - \dot{x}_2) - k_1 (x_1 - x_2) + k_2 (x_2 - w) + c_2 (\dot{x}_2 - \dot{w}) = 0 \]  

(3)

Where \( x_1, \dot{x}_1, \ddot{x}_1 \) are acceleration, velocity and displacement of the sprung mass (quarter car body mass) and \( x_2, \dot{x}_2, \ddot{x}_2 \) are acceleration, velocity and displacement of the unsprung mass respectively and \( w, \dot{w} \) are road disturbance (displacement) and velocity of wheel due to road profile. The important parameter ‘\( c_1 \)’ is the damping coefficient of sprung mass \( m_1 \), ‘\( c_2 \)’ is the damping coefficient of unsprung mass \( m_2 \). The force generated by the controller is ‘\( U_c \)’ that takes into account the road profile and vertical displacement and velocity of the vehicle. In the model, PID controller is used in Matlab Simulink to correlate the control force (\( U_c \)) exerted by the controller. A Simulink model is build using the formulation from the equation (2) and (3) as shown in figure 2.

![Figure 1: Free body diagram of quarter car model](image)
Figure 2: PID controller embedded in semi-active suspension system

To simulate and identify parameters of the suspension of car, PID controller is embedded in the semi-active suspension system. One PID controller is tuned for the displacement of the mass and other is tuned for the acceleration of the sprung mass.

4. Simulation Results and Discussions

The mathematical formulations generated from equations of motion are simulated in simulink model as shown in figure 2 with and without PID controller to compare the amplitude difference. Displacement and acceleration responses of the sprung mass with PID controller are compared with the displacement and acceleration values of a passively controlled system in suspension. The suspension parameters used in the quarter car model are shown in Table I.

| Table 1: Suspension Element Parameters |
|----------------------------------------|
| Element Parameter | Value          |
| m₁               | 240 Kg         |
| m₂               | 45 Kg          |
| k₁               | 23,000 N/m     |
| k₂               | 1,98,000 N/m   |
| c₁               | 450 N-s/m      |
| c₂               | 0              |

During simulating model, tire damping coefficient is considered as zero, neglecting tire damping for finding the performance of the system using PID controller. Step input of 0.8 m is considered for the road disturbance ‘w’ at tire. By solving the designed simulation, it is clearly observed that by defining the proportional, integral, derivative values, road disturbance at the sprung
mass can be minimized. When vehicle with passive suspension is subjected to step input at wheels, acceleration obtained is as shown in figure 3, where it takes approximately 150 seconds to come to stable position. Also highest peak point of acceleration is observed at 140 m/s². But when PID controller is applied, vehicle comes to stable position in 50 seconds with maximum acceleration of 2 m/s². Same concept of PID controller is correlated in MR damper to reduce the vibrations by controlling the damper. MR damper is controlled by supplying the current from 0.1 A to 2 A which subsequently changes the damping force. When system requires more time to settle or come to stable position, passengers in the car are subjected to vibrations for more period of time and exposure of vibration and noise for more period of time decreases the efficiency of human being. It also causes fatigue and discomfort to the passengers.

![Figure 3: Acceleration of mass m₁ without PID Controller](image)

![Figure 4: Acceleration of mass m₁ with PID Controller](image)

Same thing is observed in case of displacement of the vehicle with and without PID controller as shown in Figure 5 and Figure 6. It requires about 8 seconds for passive suspension system to become stable, whereas PID controlled system come to rest in less than 2 seconds only for the step input applied. Sprung mass in passive suspension system is displaced for the step input from 0.8m to 1.4 m (0.6m), whereas when PID controller is applied sprung mass is displaced from 0.8m to 1m (0.2m) only. Also passive suspension system behaves like under damped system, whereas PID control system looks like critically damped system coming to rest in short period of time.
5. Conclusions

The hysteresis behaviour of the MR fluid damper is formulated mathematically by developing quarter car model with PID controller in Simulink of MATLAB. The simulation result of PID controller have shown good results of vibration suppression over passively controlled damper model with the excitation signal of step input at wheels. With the PID controller, vehicle comes to stable position in 50 seconds with maximum acceleration of 2 m/s$^2$. Displacement of the system with PID controller comes to rest within short period of 2 seconds and behaves like critically damped system. This property of MR damper in suspension system provides comfort to the passengers.

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