MODELLING SIMULATION AND CONTROL OF AN ACTIVE SUSPENSION SYSTEM

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ABSTRACT

Conventional passive suspension systems lag in providing the optimum level of performance. Passive suspensions are a trade-off between the conflicting demands of comfort and control. An active suspension system provides both comfort and control along with active roll and pitch control during cornering and braking. Thus it gives a ride that is level and bump free over an incredibly rough terrain. This paper is a review the active suspension system and the modelling, simulation and control of an active suspension system in MATLAB/Simulink. The performance of the system is determined by computer simulation in MATLAB/Simulink. The performance of the system can be controlled and improved by proper tuning a proportional-integral-derivative (PID) controller. The simulation study is performed to prove the effectiveness of this control approach and the performance of the system is compared with the conventional (passive) suspension system.

Keywords: Active suspension system, Control, MATLAB/Simulink, PID controller, Simulation.

1. INTRODUCTION

The main objectives of a suspension system are to prevent the road shocks from being transmitted to the vehicle, thereby providing a suitable ride and cushioning effect to the occupants, and to keep the vehicle stable while in motion by providing good road holding (i.e. providing grip for the driver of vehicle to control its direction) during cornering and braking. But these goals are in conflict [1]. Body roll is the load transfer of a vehicle towards the outside of a turn (i.e. on the outer wheels) due to centrifugal force acting upon the car during cornering. Pitching is the tilting of the vehicle forward when weight is transferred to the front (i.e. during braking), and the tilting of the vehicle backward when weight is transferred to the rear (i.e. during acceleration). In luxury cars the suspension is usually designed with an emphasis on comfort, resulting in vehicle rolling and pitching during turning and braking. Hence, these cars are good at swallowing bumps and providing a plush ride, but the handling and control is sacrificed. In sports cars the suspension is usually designed with
an emphasis on control i.e. the suspension is designed to reduce roll and pitch, but comfort and ride quality is sacrificed. Hence, conventional suspensions are a trade-off between comfort and control of a vehicle. In order to provide both ride quality (comfort) and vehicle stability (control) active suspension systems have been developed.

1.1 Passive Suspension

Passive suspension system consists of an energy dissipating element, which is the damper, and an energy-storing element, which is the spring. Since these two elements cannot add energy to the system this is called as a passive suspension system. Passive suspension systems are subject to various tradeoffs when they are excited across a large frequency bandwidth. These are designed for a specific operating condition with a fixed spring stiffness and damping coefficient and hence do not have the ability to adjust according to different operating conditions [8].

![Passive, Semi-active and Active Suspension Systems](image)

**Fig. 1:** Passive, Semi-active and Active Suspension Systems

1.2 Semi active Suspension

Semi active suspension system is the adaptation of the damping and/or the stiffness of the spring to the actual demands. Semi-active control is particularly advantageous in vehicle suspension systems due to its low energy consumption. Hence, to replace complexity and cost while improving ride and handling the concept of semi active suspension has emerged. In this kind of suspension system, usually the passive suspension spring is retained, while the damping force in the damper can be modulated in accordance with operating conditions. Electro Rheological (ER) and Magnetic Rheological fluid dampers [2] are preferred as they have the ability to change their damping coefficient.

1.3 Active Suspension

In contrast to passive systems, active suspension systems can adjust their dynamic characteristics in response to varying road conditions in real time, and offer superior handling, road feel and responsiveness as well as roll stability and safety without compromising ride quality. Active suspension systems provide an extra force input in addition to possible existing passive systems by the incorporation of an actuator in parallel with the mechanical spring. Both electromagnetic and hydraulic actuators can be used, but generally electromagnetic actuators are preferred due to its quick response and speed of actuation. As opposed to the passive control, active control can improve the performance over a wide range of frequencies. However, active vibration control has the
disadvantages of complexity and high energy consumption. This system is explained in detail in the next section.

The outline of the paper is as follows. Section 2 gives a detailed description of the active suspension system. Quarter car test setup is discussed in section 3, which is the basis for suspension system modelling that is discussed in section 4. Section 5 and section 6 deal with the modelling and control of the suspension system respectively. Section 7 compares the performance of the active and passive suspension systems. Conclusion is presented in section 8.

2. ACTIVE SUSPENSION SYSTEM

The active suspension system works as a closed loop control system. The active suspension system consists of four important components viz.

2.1 Linear Electromagnetic Motor (LEM)

A high bandwidth linear electromagnetic motor is installed at each wheel of the vehicle with active suspension system. Inside the LEM, magnets and coils of wire are installed. When electrical power is applied to the coils, the motor retracts and extends, creating motion between the wheel and the car body. Thus electrical energy is converted into linear mechanical force and motion. The LEM can counteract the body motion of a car while accelerating, braking and cornering, thus ensuring vehicle control. It also responds quickly enough to counter the effects of bumps and potholes, thus ensuring passenger comfort [3]. The motor is strong enough to put out enough force to prevent car from rolling and pitching during aggressive driving maneuvers. In addition to the motor, the wheel dampers inside each wheel hub further smooth out road imperfections. Torsion bars take care of supporting the vehicle, thus optimizing handling and ride dynamics.

![Fig. 2: Conventional (Passive) and Active Suspension System](image)

The LEM is essentially a multi-phase alternating current (AC) electric motor that has its stator unrolled. Thus, instead of producing a torque (rotation) it produces a linear force along its length. It has the ability to extend (as if into a pothole) & retract (as if over a bump) with much greater speed than any fluid damper (taking just milliseconds). These lightning fast reflexes and speed along with the precise movement finely controls motion of the wheel. Thus, the body of the car remains level, regardless of the terrain. This is also a failsafe system because this system will still continue to function as a passive suspension system even if the power supply to the LEM is cut off.
2.2 Sensors

A sensor measures a physical parameter (vertical displacement, acceleration and velocity) and decodes it into an electrical signal. In this system three types of sensors are used. The sensor measurements are used to instantaneously counteract the road forces. The sprung mass acceleration sensor gives a direct measure of comfort of the vehicle. The suspension travel sensor gives direct measure of suspension travel, which is the measure of distance from the bottom of the suspension stroke (when the vehicle is on a jack and the wheel hangs freely) to the top of the suspension stroke (when the vehicle's wheel can no longer travel in an upward direction toward the vehicle). This sensor is aligned with the passive spring and damper and hence the stroke can be measured directly [4]. The unsprung mass acceleration sensor is installed to estimate the state of the tyre since it is not possible to measure the tyre compression directly. Thus, this set of three sensors provides all the information needed for the operation of the system.

2.3 Power Amplifier

A bidirectional power amplifier sends the power to the LEM during extension and the LEM returns the power to the amplifier during retraction. The electrical power is delivered to the LEM by a power amplifier in response to signals from the control algorithms. The system uses compressive force to recover the energy or power, and store it either in the engine battery or in some other external storage device. Thus, when the suspension encounters a pothole, power is used to extend the motor and isolate the vehicle’s occupants from the disturbance. On the far side of the pothole, the motor operates as a generator and returns the power back through the amplifier. This regenerative action results in a very efficient suspension system design.

2.4 Control Algorithms

The sensor measurements are used by the control algorithms and they send command to the power amplifiers which in turn operate the LEM. These electrical signals from the sensors are processed by the PID and it generates a control signal which controls the action of the actuator for fine response in real time.

3. QUARTER CAR TEST SETUP

![Fig. 3: Quarter Car Test Setup](image)

![Fig. 4: Quarter Car Model](image)
The quarter car model suspension system consists of one-fourth of the body mass, suspension components and one wheel. The on road measurements are reproduced on a quarter car test setup. In Fig. 3, the alphabets represent different components [5]. Here, 'a' represents the road shaker which performs the road excitations, 'b' represents the coil spring representing the tyre stiffness, 'c' represents the unsprung mass, 'd' represents the active suspension system which connects sprung mass and the unsprung mass, and 'e' represents the sprung mass. This is also represented symbolically in Fig 4. Quarter car models simplify the analysis and represent most of the features of the full scale model.

4. SYSTEM MODELLING

The differential equations of motion for the two degree of freedom systems shown in Fig. 5 are written by using Newton’s Second Law of Motion and the free body diagram approach and the mathematical model is derived [11]. For passive quarter car model, the equations for the sprung and unsprung masses may be written as

$$M_s \ddot{x}_s = -k_s (x_s - x_{us}) - b_s (\dot{x}_s - \dot{x}_{us})$$  \hspace{1cm} - (1)

$$M_{us} \ddot{x}_{us} = k_s (x_s - x_{us}) + b_s (\dot{x}_s - \dot{x}_{us}) - k_t (x_{us} - r)$$  \hspace{1cm} - (2)

For active quarter car model, the equations for the sprung and unsprung masses may be written as

$$M_s \ddot{x}_s = -k_s (x_s - x_{us}) - b_s (\dot{x}_s - f)$$  \hspace{1cm} - (3)

$$M_{us} \ddot{x}_{us} = k_s (x_s - x_{us}) + b_s (f - \dot{x}_{us}) - k_t (x_{us} - r)$$  \hspace{1cm} - (4)

where,

- $M_s$ = Sprung mass (kg)
- $x_s$ = Sprung mass displacement (m)
- $M_{us}$ = Unsprung mass (kg)
- $x_{us}$ = Unsprung mass displacement (m)
- $k_s$ = Spring stiffness constant (N/m)
- $b_s$ = Damping coefficient (Ns/m)
- $k_t$ = Tyre stiffness constant (N/m)
- $r$ = Road input (m)
- $f$ = Actuator control force (N)
In the above representation of the passive and active suspension systems, tyre is modelled as a linear spring without damping. The road input \( r \) is considered as the disturbance signal. The actuator control force \( f \) is introduced in the system by the LEM, between the body mass (sprung mass) and the wheel mass (unsprung mass).

5. SIMULATION

Mathematical modelling is transformed into a computer simulation model and MATLAB/Simulink is used for the simulation. Simulink is a versatile interface that can handle various types of controllers easily. It helps in dynamic performance analysis of a system by construction of a basic suspension model along with the implementation a controller integrated within the system [6]. The Simulink library is utilized and the logic is developed according to the mathematical model to simulate the system in Simulink. The passive suspension system model in Simulink is based on the equation (1) and (2). This is an open loop system with no feedback element for appropriate adjustment of the parameters. The active suspension system model in Simulink is based on the equation (3) and (4). In this system, the actuator force is controlled by the PID, thus involving a feedback loop.

![Fig. 6: Settling Time and Overshoot for PID](image)

A road disturbance (e.g. a bump) is simulated. The simulated model is analyzed after running it to a predefined time and different observations are drawn regarding the performance and behaviour of suspension system. The recovery from the disturbance is plotted for the passive suspension system, and the active suspension system a proportional-integral-derivative (PID) controller when controller is implemented. The overshoot and settling time as shown in Fig. 6 are the factors governing passenger comfort and vehicle control and vehicle stability. Thus, the overshoot and settling time should be minimized by proper tuning of a PID controller.

6. SYSTEM CONTROL

Various control approaches can be applied for the control of the active suspension system. In this paper, the PID controller is considered for providing the fine control of the suspension system. Due to their simple structure and robust performance, PID controllers are the most commonly used controllers in process control applications. The transfer function of a PID controller has the following form.
PID controller used in the active suspension is a closed loop system. The strength of PID approach is that the factors of the performance index can be weighted according to the designer’s desires or other constraints using it. In this study, the PID method is used to improve the road handling and the ride comfort for a quarter car model [7]. PID is tuned so that the response for the step input disturbance is good. The controller structure adopted in this study is shown in Fig. 8.

![Fig. 7: PID as a Feedback Loop Control](image)

![Fig. 8: Controller Architecture](image)

For designing a PID controller, the following steps are executed to obtain a desired response:
1. Obtain an open-loop response and determine what needs to be improved
2. Add a proportional control to improve the rise time
3. Add a derivative control to improve the overshoot
4. Add an integral control to eliminate the steady-state error
5. Adjust each of $K_P$, $K_D$, $K_I$ until a desired overall response is obtained

In the PID feedback loop control system, an error signal is fed to the PID to adjust the input to the actuator so that the output reaches to the desired set point as shown in fig. 7. This error signal is the difference between desired and actual values. The success of the PID controller depends on appropriate choice of the PID gains. There are three gains - Proportional $K_P$, Integral $K_I$ and derivative gain $K_D$ - which can be easily adjusted in order to provide fine control for the application. The effects of each of 3 controller parameters on a closed loop system are summarized in the Table 1. Note that these correlations may not be exactly accurate because the three are dependent on each other.

For fine tuning of the controller in order to reducing the overshoot and settling time, the following gain values are taken into consideration - $K_P=1000$, $K_D =4000$ & $K_I =5000$. The above selected values of gains are taken into account by adjusting them manually in Simulink where the minimum overshoot and as well as the minimum settling time is obtained, while Simulink platform also has a provision by which it can auto tune the gains. The manual tuning is carried out by taking into account the criteria mentioned in Table 1.
Table No. 1: Gain Variation with Different Factors for Tuning of PID

<table>
<thead>
<tr>
<th>Controller Response</th>
<th>Rise Time</th>
<th>Overshoot</th>
<th>Settling Time</th>
<th>Steady State Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_P$</td>
<td>Decrease</td>
<td>Increase</td>
<td>Small Change</td>
<td>Decrease</td>
</tr>
<tr>
<td>$K_I$</td>
<td>Decrease</td>
<td>Increase</td>
<td>Increase</td>
<td>Eliminate</td>
</tr>
<tr>
<td>$K_D$</td>
<td>Small Change</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Small Change</td>
</tr>
</tbody>
</table>

7. RESULTS AND DISCUSSIONS

From Fig. 9 it can be seen that the settling time for a passive system is 100sec [9]. Fig. 10 gives the settling time of the active suspension system as 8sec for the same road input.

Reduction in settling time = (passive value – active value) / passive value = (100 - 8)/100 = 92%

Thus, the settling time is reduced by 92% in case of an active suspension system.

The flat road surface with a sinusoidal concave bump followed by a sinusoidal convex bump [10] shown in Fig.11 is the road disturbance. Fig. 12 gives the simulated response for the active and passive suspension systems. This is a close approximation of the actual situation. We can notice that the oscillations of active suspension system are less than passive suspension system.
From Fig. 12, it can be seen that the peak overshoot of sprung mass displacement for passive system is 0.04 m while that for the active suspension system it is 0.018 m for the same road input. Reduction in peak value = (passive value – active value) / passive value = (0.04 - 0.018)/0.04 = 55%

Thus, the sprung mass displacement (or overshoot) is reduced by 55% in case of an active suspension system. This is a direct indication of the superiority of the active suspension over the passive suspension system.

Table No. 2: Comparison of Passive and Active Suspension Systems

<table>
<thead>
<tr>
<th>Performance Parameters</th>
<th>Passive Suspension</th>
<th>Active Suspension</th>
<th>Reduction (Improvement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung Mass Displacement OR Overshoot (m)</td>
<td>0.04</td>
<td>0.018</td>
<td>55%</td>
</tr>
<tr>
<td>Settling Time (sec)</td>
<td>100</td>
<td>8</td>
<td>92%</td>
</tr>
</tbody>
</table>

8. CONCLUSION

1. Active suspension systems can maintain the required stability and comfort due to the ability of adaptation in correspondence with the state of vehicle in real time.
2. The proposed PID control gives 55% reduction in body vertical displacement for the same road input, thus improving passenger comfort.
3. The proposed PID control gives 92% reduction in settling time for the same road input, thus improving vehicle stability, control and passenger safety.
4. As both overshoot and settling time is reduced, active suspensions provide much better dynamic performance as compared to the passive suspension system.
5. The simulation results prove that the PID control technique used is effective.

REFERENCES


