

Development of a Semi-Active Suspension Controller Using Adaptive-Fuzzy with Kalman Filter

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ABSTRACT

Following the developments in controlled suspension system components, the studies on the vertical dynamics analysis of vehicles increased their popularity in recent years. The objective of this study is to develop a semi-active suspension system controller using Adaptive-Fuzzy Logic control theories together with Kalman Filter for state estimation. A quarter vehicle ride dynamics model is constructed and validated through laboratory tests performed on a hydraulic four-poster shaker. A Kalman Filter algorithm is constructed for bounce velocity estimation, and its accuracy is verified through measurements performed with external displacement sensors. The benefit of using adaptive control with Fuzzy-Logic to maintain the optimal performance over a wide range of road inputs is enhanced by the accuracy of Kalman Filter in estimating the controller inputs. A gradient-based optimization algorithm is applied for improving the Fuzzy-Logic controller parameters. The vehicle model is simulated with the developed semi-active suspension controller on different road profiles. A comparison is performed between the Adaptive-Fuzzy semi-active controller, the optimal LQR semi-active controller, and the optimal passive suspension system in terms of ride comfort and road holding. The results showed that, the proposed semi-active suspension system controller provides significant improvements in both ride comfort and road holding of the vehicle on different road profiles.

INTRODUCTION

Nowadays, the semi-active suspension systems are used to offer solutions for overcoming the ride performance limitations of passive suspension systems in one hand, and on the other hand for reducing the high system cost and energy consumption of fully active suspension systems. The

hardware and the control equipments of an active suspension system are also required for a semi-active system, however the actuator, hydraulic pumps and accumulators are replaced with a controllable damper. The semi-active systems can clearly offer cheaper suspension control solutions compared to the active systems. However, this is achieved at the expense of reduced ride comfort and road holding performance. The objective that attracts the current research studies is to improve the performance of semi-active control systems through different control approaches.

A wide variety of semi-active suspension systems have been investigated theoretically and experimentally using different types of control methods. The development of semi-active suspensions using shock absorbers with multiple damping curves associated with leveling springs has been presented by Vannucci [1]. He described the characteristics of the control logic employed, the shock absorber design, and the leveling system. In addition, he presented a matrix control logic, sensors to be used, and design alternatives for improving ride comfort and stability of passenger vehicle suspensions. Soliman and Crolla [2] used a quarter vehicle model with linear quadratic regulator (LQR) control technique for a semi-active suspension system including a look-ahead preview algorithm. The performance of a semi-active suspension system with preview control is compared with an active system with and without preview control, and with a passive suspension system. They concluded that, the performance of a semi-active suspension can be improved significantly if preview information about the road input, ahead of the wheel is available. One of the most important findings in their study is that, the performance of the semi-active system with preview is as good as the performance of the active system without preview. However, practical problems still exist in the measurement of the road surface height ahead of the front wheels. Wu et al. [3] presented a semi-active vehicle

suspension system using an adjustable shock absorber applied on a quarter vehicle model. They developed two control techniques for assessing both ride comfort and road handling. Apart from the proportional-integral-derivative (PID) controller, a controller using Fuzzy-Logic is developed and its performance is experimentally tested. The simulation results showed that, the semi-active control provides lower root mean square (RMS) values and reduced settling time compared to the passive suspension system. It was demonstrated that, the proposed Fuzzy-Logic controller achieves much better performance compared to the semi-active suspension with PID controller and the passive suspension under various road conditions. In addition to this, the experimental tests indicated that, both the PID controller and the Fuzzy-Logic controller effectively suppress the vibration of the proposed quarter vehicle model for various road conditions. A new methodology to design a semi-active suspension controller through the *linear parameter variation* (LPV) technique was introduced by Poussot et al. [4]. This new approach provides some advantages compared to the existing methods in terms of performance, flexibility, and robustness. They performed simulations with a nonlinear quarter vehicle model to show the efficiency of the method and to validate the theoretical approach. Moreover, it is claimed that the implementation of such a controller results in a cheap solution. Giua et al. [5] presented a two-phase design technique for semi-active suspensions where the shock absorber is a solenoid valve damper. The first phase of this technique is called *unconstrained update control* (UUC), and it includes the design of a “target active control law” obtained from the solution of the LQR problem. In the second phase, which is called *incremental update control* (IUC), this target law is approximated by controlling the damper coefficient of the semi-active suspension. The proposed procedure has been applied to a quarter vehicle model. They concluded that, in all cases the semi-active suspension system provides a good approximation of the fully active suspension system, while producing significant improvements compared to the passive suspension system. Zhang et al. [6] developed, modeled, and tested Skyhook and MiniMax control strategies for a semi-active suspension. The control performances are investigated using a quarter vehicle model. The comparison and evaluation of the control results are performed using software-in-the-loop simulations (SIL). The simulation results showed that, the Skyhook control can provide considerable reduction in the resonant peak of the body mass compared to the passive suspension and the MiniMax controller. On the other hand, it is also possible to increase or decrease the wheel load by using MiniMax controller to improve the safety of the vehicle. The influence of road roughness on the ride comfort of a vehicle employing semi-active suspension system is investigated by Soliman [7]. The mathematical model of a quarter vehicle with semi-active suspension system has been developed for vehicle ride comfort evaluation. The power consumption due to rolling resistance and the power dissipation in the suspension have

been evaluated for passive and semi-active suspensions. The obtained results showed that the ride comfort is improved as the road roughness is decreased.

In this study, a semi-active suspension system controller using Adaptive-Fuzzy control theories together with Kalman Filter for state estimation is developed. A quarter vehicle ride dynamics model is developed and validated through laboratory tests performed on a hydraulic four-poster shaker. The bounce velocity estimation algorithm is also verified through measurements. The performance of the developed semi-active suspension controller is compared with the performance of the optimal passive and the optimal LQR controlled semi-active suspensions. The performance comparison is based on the power spectral density (PSD) of the weighted body acceleration and the dynamic tyre load.

MATHEMATICAL MODEL OF THE VEHICLE

PASSIVE SUSPENSION SYSTEM MODEL

In this study, the vehicle with passive suspension system is modeled as a two degree of freedom model consisting of two masses which represent the body and wheel masses. The suspension between body mass and wheel mass is modeled as a linear spring and a viscous damper as shown in [Figure 1](#). The nonlinear characteristics of the damper are taken into account. The tyre is modeled by using a non-linear spring and a linear damper connected in parallel. Point contact is assumed between the road and the tyre.

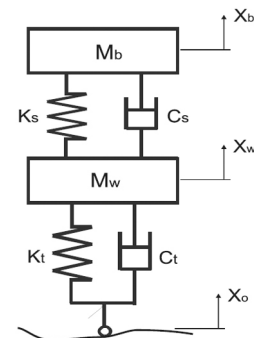


Figure 1. Passive suspension system model.

The dynamic equations of motion of the quarter vehicle model are written as follows:

$$M_b \ddot{X}_b = -K_s(X_b - X_w) - C_s(\dot{X}_b - \dot{X}_w) \quad (1)$$

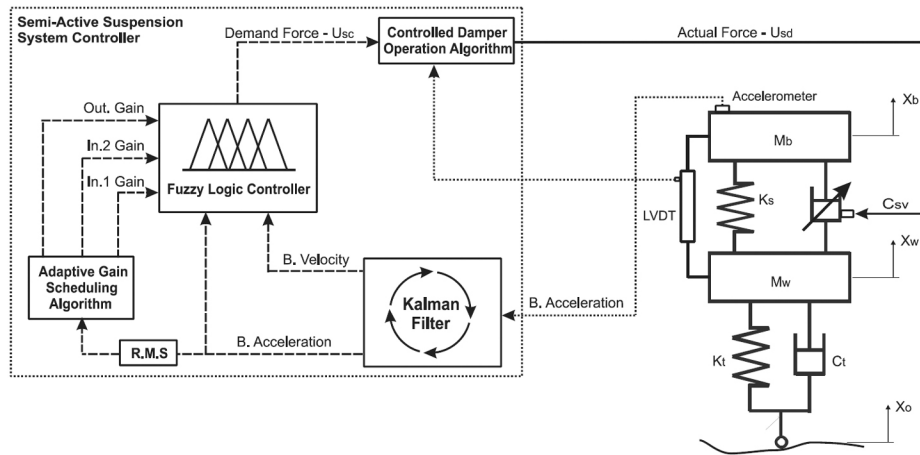


Figure 2. Semi-active suspension system model with control scheme.

$$M_w \ddot{X}_w = -K_t(X_w - X_o) - C_t(\dot{X}_w - \dot{X}_o) + K_s(X_b - X_w) + C_s(\dot{X}_b - \dot{X}_w) \quad (2)$$

In the above equations, M_b and M_w represent the body and wheel masses, K_s and K_t represent the suspension and tyre stiffness, C_s stands for the damping coefficient which is a function of the damper velocity, and C_t is the tyre damping coefficient. The body, wheel, and road displacements are denoted as X_b , X_w , and X_o , respectively, and they are given with respect to the inertial frame.

SEMI-ACTIVE SUSPENSION SYSTEM MODEL

The quarter vehicle model with the semi-active suspension system is constructed by replacing the conventional damper of the passive system with a controllable damper. The spring and the controllable damper are fitted in parallel between the body and wheel mass, as shown in Figure 2. By denoting the controllable damper force as U_{sd} , the equations of motion for the semi-active suspension system can be written as given with Equations from 3,4,5. The value of the damping coefficient C_{sv} is determined by the semi-active suspension system controller.

$$M_b \ddot{X}_b = -K_s(X_b - X_w) - U_{sd} \quad (3)$$

$$M_w \ddot{X}_w = -K_t(X_w - X_o) - C_t(\dot{X}_w - \dot{X}_o) + K_s(X_b - X_w) + U_{sd} \quad (4)$$

$$U_{sd} = C_{sv}(\dot{X}_b - \dot{X}_w) \quad (5)$$

CONTROL SYSTEM DESCRIPTION

The controllable damper used in the semi-active suspension system can be controlled continuously between upper and lower limits of the force-velocity characteristic curves. Therefore, it is theoretically capable of tracking a force demand signal independently of the damper velocity. The demanded suspension force U_{sc} is generated by the controller according to different control laws and strategies. However, since the controller output cannot be fully implemented because of the non-linear restriction in the system, i.e. it can only dissipate energy and not input it, the system cannot work with the output control signal only [8]. Therefore, an additional control law is required to keep the control force in the controllable damper limits. In this study, Adaptive-Fuzzy control with Kalman Filter has been used to construct a controller for generating the demanded suspension control force U_{sc} . The additional control law defined with the Equations from 6,7,8,9 is used to keep the demanded damper force always within the limits of the controllable damper [2].

$$\text{If } (\dot{X}_b - \dot{X}_w) \cdot U_{sc} < 0 \quad \text{then} \quad C_{sv} = C_{min} \quad (6)$$

$$\text{If } (\dot{X}_b - \dot{X}_w) \cdot U_{sc} < C_{min} \quad \text{then} \quad C_{sv} = C_{min} \quad (7)$$

$$\text{If } (\dot{X}_b - \dot{X}_w) \cdot U_{sc} > C_{max} \quad \text{then} \quad C_{sv} = C_{max} \quad (8)$$

$$\text{else} \quad C_{sv} = \frac{U_{sc}}{(\dot{X}_b - \dot{X}_w)} \quad (9)$$

The control process, shown in Figure 2, starts with the Kalman Filter which provides the estimated body velocity and acceleration to the Adaptive-Fuzzy controller. The

adaptive gain scheduling algorithm selects the optimal Fuzzy-Logic input and output gains according to the RMS value of body acceleration rate. The Fuzzy-Logic controller uses the estimated body velocity and acceleration to generate the demanded suspension force U_{sc} . The additional semi-active damper control law is used to calculate the value of the damping coefficient C_{sv} which is inside the controllable damper limits, according to the demanded control signal U_{sc} and the damper velocity. The damper control signal is filtered with a 5 Hz low-pass filter considering the physical limits of the controller and the damper valve. The vehicle model is used to calculate the body acceleration and suspension working space, which are then feedback to the control system.

ADAPTIVE-FUZZY LOGIC CONTROLLER

FUZZY-LOGIC CONTROLLER

In this research study, the Fuzzy-Logic is used for semi-active suspension control. The Fuzzy-Logic, which is one of the most intelligent control methods, offers several unique features that make it particularly good choice for many control problems. It can be used to control nonlinear systems which are difficult or impossible to model mathematically. In addition to this, it does not require precise, noise-free inputs, and can be programmed to control the system safely if a feedback sensor quits or destroyed. The control output is a smooth function despite a wide range of input variations. Therefore, any sensor data that provides some indication of the system actions and reactions is sufficient. In other words, the Fuzzy-Logic control allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low [9, 10]. Because of these advantages, the Fuzzy-Logic control is used in this study for the development of a semi-active suspension system controller. The *rule base* and *interface engine* are based on Mamdani-Type of fuzzy inference, while the defuzzification process is based on *center of area* method. This controller uses the body vertical acceleration and velocity as the input signals and generates the suspension force demand signal U_{sc} . A gradient-based optimization routine is used to optimize the controller input and output gains. The objective of optimization is to minimize the body acceleration and dynamic tyre load, whilst at the same time maintain the suspension working space in the allowable limits. The following performance index is used for the optimization process.

$$PI = 0.5 \int_{t_0}^{\infty} q_1 (X_b - X_w)^2 + q_2 (X_w - X_o)^2 + q_3 \ddot{X}_b + \rho U_s^2 \quad (10)$$

where; q_1 , q_2 , q_3 , and ρ are the weighting parameters. The surface view of the Fuzzy-Logic semi-active suspension system controller is shown in Figure 3.

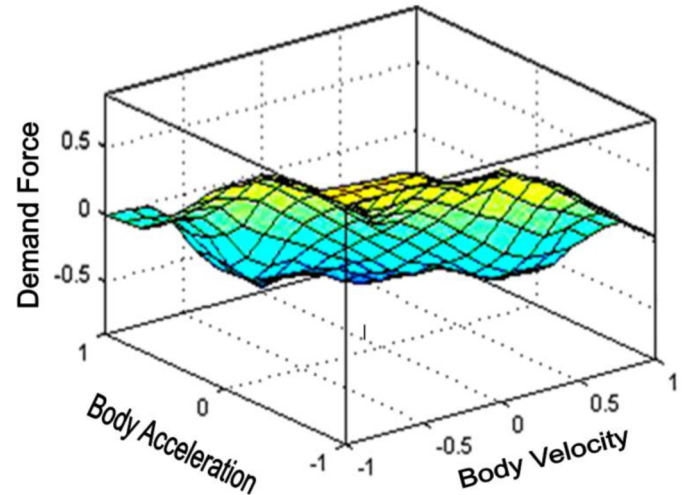


Figure 3. Fuzzy-Logic controller surface view.

ADAPTIVE GAIN SCHEDULING TECHNIQUE

Adaptive gain scheduling is one of the well-known adaptation techniques used in vehicle dynamics control applications [11]. The aim of the adaptation algorithm is to maintain the optimal performance over a wide range of inputs. In this study, an adaptive gain scheduling technique is used for selecting the optimal Fuzzy-Logic input and output gains according to the RMS value of the rate of body acceleration as shown in Table 1. The semi-active suspension model is simulated over a variety of different roads and the adaptation gains of the Fuzzy-Logic controller are tuned to provide further performance improvement.

Table 1. Adaptive gain scheduling algorithm based on the RMS of body vertical jerk.

RMS of Body Vertical Jerk [m/s ³]	Current set	Input 1 gain	Input 2 gain	Output gain
0-10	1	g11	g12	g13
10-25	2	g21	g22	g23
25-50	3	g31	g32	g33
> 50	4	g41	g42	g43

KALMAN FILTER FOR VELOCITY ESTIMATION

State estimation is an essential part of the active and semi-active suspension control. Commonly measured ride states during road operation are the body and wheel accelerations, and the suspension working space. Since body velocity is difficult to measure directly, it is estimated from the measurable states by using filtering and state estimation