

Rule Optimized Fuzzy Logic Controller for Full Vehicle Semi-Active Suspension

Mina M.S. Kaldas, Kemal Çalışkan, Roman Henze and Ferit Küçükay
IAE, TU Braunschweig

ABSTRACT

This paper presents a new and effective control concept for semi-active suspension systems. The proposed controller uses a Fuzzy Logic scheme which offers new opportunities in the improvement of vehicle ride performance. The Fuzzy Logic scheme tunes the controller to treat the conflict requirements of ride comfort and road holding parameters within a specified range of the suspension deflection. An eleven degree of freedom full vehicle ride dynamics model is constructed and validated through laboratory tests performed on a hydraulic four-poster shaker. A new optimization process for obtaining the optimum Fuzzy Logic membership functions and the optimum rule-base of the proposed semi-active suspension controller is proposed. Discrete optimization has been performed with a Genetic Algorithm (GA) to find the global optima of the cost function which considers the ride comfort and road holding performance of the full vehicle. The proposed Fuzzy Logic semi-active controller is compared to the optimum Linear Quadratic Regulator (LQR) semi-active controller and the optimum 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 performance of the vehicle.

CITATION: Kaldas, M., Çalışkan, K., Henze, R. and Küçükay, F., "Rule Optimized Fuzzy Logic Controller for Full Vehicle Semi-Active Suspension," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):2013, doi:10.4271/2013-01-0991.

INTRODUCTION

Several different control methods have been studied and applied to the active/semi-active suspension systems. Karnopp et al. [1] have proposed the famous 'skyhook' damper control algorithm for a vehicle suspension system and demonstrated that this system offers improved performance over a passive system. Ahmadian [2] had modified the skyhook strategy by combining it with groundhook strategy to improve road holding performance parallel to the ride comfort. Soliman and Crolla [3] proposed a self-tuning LQR control algorithm for a switchable damper suspension system. The controller provides the set of gains over different operating conditions, and is based on the adapted estimates of vehicle parameters and states, and the adapted weighting parameters. A quarter vehicle model for the switchable damper suspension system has been used. The effect of extreme cases with a fixed gain controller for the switchable damper suspension system is investigated. The results showed that the switchable damper with self-tuning gives a significant improvement over fixed gains and a passive suspension system.

The control performance of traditional controllers depends mainly on the accuracy of the dynamic model used

and the accuracy of the state measurements and estimates. In order to meet practical requirements in a semi-active suspension system, it is crucial to derive or to identify an appropriate model for the traditional controller design. Estimating uncertain effects is even more challenging due to the random noise caused by road inputs [4,5,6].

Some model-free and robust intelligent controllers were introduced to solve the problems of the uncertainty effects, e.g. Fuzzy Logic Controller (FLC) [7, 8]. The FLC is an adequate methodology for designing robust controllers that are capable of delivering a satisfactory performance in the face of uncertainty and imprecision. As a result, the FLC has become a popular approach to non-linear and uncertain system control in recent years. There are different ways to construct FLCs for vehicle suspension control, with the most common method to construct the FLCs being by eliciting the fuzzy rules and its membership functions based on experts' knowledge or experience [9, 10]. Huang et al. [11] proposed an adaptive FLC for an active suspension system. The inputs of the FLC are the vertical position error of the vehicle sprung mass and the rate of change of this error, while the output is the damper control voltage. The antecedents membership functions consists of 11 equal triangular type

functions. The voltage increment membership function is a set of 15 equal triangular type functions. The self-tuning property is implemented by adjusted scaling factors for controller inputs and output. One hundred and twenty one fuzzy rules are employed to suppress the sprung mass vibration amplitude due to road inputs. In order to evaluate the fuzzy control system, a 2 DOF quarter-vehicle suspension model was used. The dynamic response of the semi-active suspension system was presented for vehicle ride performance on a rough concave-convex road with 25mm obstacles but not compared with the known control strategies. It was noted that the control signal was very smooth and easy to employ in the practical vehicle. The adjusted scaling factors were chosen by experiments and many simulations, which limit the flexible and adaptive abilities of the adaptive FLC.

Wu et al. [12] presented a semi-active vehicle suspension system using an adjustable shock absorber applied on a quarter vehicle model. Two control techniques for assessing both ride comfort and road handling have been developed. 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 FLC 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 FLC effectively suppress the vibration of the proposed quarter vehicle model for various road conditions.

Kaldas et al. [13] developed a semi-active suspension system controller using Adaptive Fuzzy Logic control theories together with a 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 optimum performance over a wide range of road inputs is enhanced by the accuracy of the Kalman Filter in estimating the controller inputs. A gradient-based optimization algorithm is applied for improving the FLC 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 optimum LQR semi-active controller, and the optimum 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.

The common problem of the available fuzzy controllers for suspension control is that using the experts' knowledge or experience to design the fuzzy controller rule base cannot fully handle or accommodate for the uncertainties associated with changing road inputs. Therefore, the automatic design methods and rule acquisition procedures for fuzzy systems are required and have been proposed mostly based on GA. The key advantage of the hybrid system combining GA and FL is that almost all the tasks of fuzzy system design can be accomplished automatically. The FL parameters of inference rules and membership functions are able to be determined by a hybrid system itself [14, 15].

In this study, a new and effective control concept for semi-active suspension system is presented. The proposed Fuzzy Logic scheme tunes the controller to treat the conflicting requirements of ride comfort and road holding parameters within a specified range of the suspension deflection. An experimentally verified full vehicle ride dynamics model is used for evaluating the performance of the proposed FLC. The Fuzzy Logic membership functions and the rule-base of the proposed semi-active suspension controller are obtained through a unique discrete optimization process. A GA has been used to find the global optima of the cost function, which considers the ride comfort and road holding performance of the full vehicle.

VEHICLE MODEL

Full Vehicle Vertical Dynamics Model

In this study, a generic full vehicle suspension model with non-linear suspension component characteristics has been used. The vehicle model contains seven masses, which represent the body, four wheels, engine and driver. The model has eleven DOF which, include the bounce, pitch and roll motions of the body and engine, and the bounce motion of the wheels and driver. The suspension between the body mass and the wheel mass is modeled using a linear spring, and a viscous damper in series with a rubber top mount, at each corner. The damper and top mount masses are neglected. The nonlinear characteristics of the damper and the top mount are taken into account by using a detailed damper top mount model and non-linear Force-Velocity damper characteristics [16]. The tyre is modeled with a non-parametric Force-Displacement-Velocity map, and a point contact is assumed between the road and the tyre at each corner. Tyre-road separation is taken into account. Furthermore, the anti-roll bars at front and rear axles are also considered in the model. The engine is assumed to have bounce, pitch and roll degrees of freedom with respect to the vehicle body. The engine body is supported by three equivalent vertical mounts, which are modeled using linear springs in parallel with viscous dampers. The driver is included inside the full vehicle model as a one DOF system with vertical motion only, and it is modeled as a mass supported by a linear spring and a linear damper. The axis

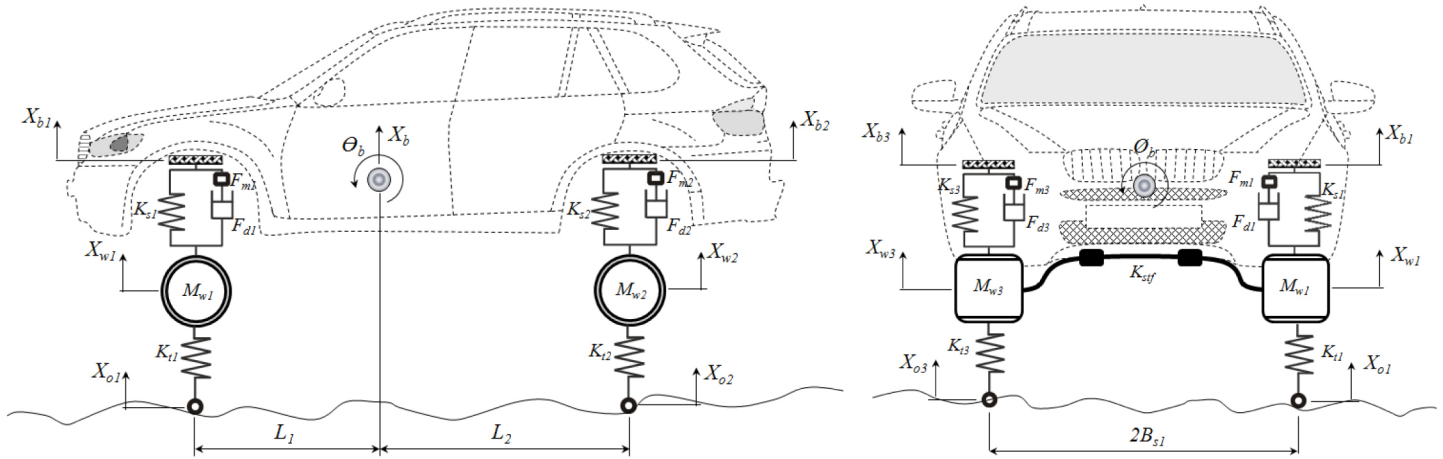


Figure 1. Vehicle model

convention and the notations used for the vehicle body, wheels and road profile are shown in Figure 1.

The equations of motion for the bounce, pitch and roll responses of the vehicle body are written as follows:

$$M_b \ddot{X}_b = -F_{sb1} - F_{sb2} - F_{sb3} - F_{sb4} + F_{e1} + F_{e2} + F_{e3} + F_s \quad (1)$$

$$I_b \ddot{\theta}_b = L_1 F_{sb1} - L_2 F_{sb2} + L_1 F_{sb3} - L_2 F_{sb4} + T_e^p + T_s^p \quad (2)$$

$$J_b \ddot{\varphi}_b = B_{s1} F_{sb1} + B_{s2} F_{sb2} - B_{s1} F_{sb3} - B_{s2} F_{sb4} + T_{stf} + T_{str} + T_e^r + T_s^r \quad (3)$$

The equations of motion for the engine vertical, pitch and roll responses are:

$$M_e \ddot{X}_e = -F_{e1} - F_{e2} - F_{e3} \quad (4)$$

$$I_e \ddot{\theta}_e = L_{e1} F_{e1} - L_{e2} F_{e2} - L_{e3} F_{e3} \quad (5)$$

$$J_e \ddot{\varphi}_e = B_{e1} F_{e1} - B_{e2} F_{e2} - B_{e3} F_{e3} \quad (6)$$

The equations of motion for the driver seat vertical response can be written as:

$$M_s \ddot{X}_s = -F_s \quad (7)$$

The equations of motion for the bounce motion of the wheels can be written as:

$$M_{wi} \ddot{X}_{wi} = -F_{wi} + F_{swi} \quad (8)$$

where;

$$X_{b1} = X_b - L_1 \theta_b + B_{s1} \varphi_b \quad (9.a)$$

$$X_{b2} = X_b + L_2 \theta_b + B_{s2} \varphi_b \quad (9.b)$$

$$X_{b3} = X_b - L_1 \theta_b - B_{s1} \varphi_b \quad (9.c)$$

$$X_{b4} = X_b + L_2 \theta_b - B_{s2} \varphi_b \quad (9.d)$$

$$X_{e1} = X_e - L_{e1} \theta_e + B_{e1} \varphi_e \quad (10.a)$$

$$X_{e2} = X_e - L_{e2} \theta_e - B_{e2} \varphi_e \quad (10.b)$$

$$X_{e3} = X_e + L_{e3} \theta_e - B_{e3} \varphi_e \quad (10.c)$$

$$X_{be1} = X_b - L_{be1} \theta_b + B_{be1} \varphi_b \quad (11.a)$$

$$X_{be2} = X_b - L_{be2} \theta_b - B_{be2} \varphi_b \quad (11.b)$$

$$X_{be3} = X_b - L_{be3} \theta_b - B_{be3} \varphi_b \quad (11.c)$$

$$X_{bs} = X_b - L_{bs} \theta_b + B_{bs} \varphi_b \quad (12)$$

$$F_{sbi} = K_{si} (X_{bi} - X_{wi}) + F_{mi} \quad (13)$$

$$F_{ej} = K_{ej} (X_{ej} - X_{bej}) + C_{ej} (\dot{X}_{ej} - \dot{X}_{bej}) \quad (14)$$

$$F_s = K_s (X_s - X_{bs}) + C_s (\dot{X}_s - \dot{X}_{bs}) \quad (15)$$

$$F_{wi} = K_{ti} (X_{wi} - X_{oi}) \quad (16)$$

$$F_{swi} = K_{si}(X_{bi} - X_{wi}) + F_{di} \quad (17)$$

$$T_e^p = -L_{be1}F_{e1} - L_{be2}F_{e2} - L_{be3}F_{e3} \quad (18)$$

$$T_e^r = B_{be1}F_{e1} - B_{be2}F_{e2} - B_{be3}F_{e3} \quad (19)$$

$$T_s^p = -F_s L_{bs} \quad (20)$$

$$T_s^r = F_s B_{bs} \quad (21)$$

$$T_{stf} = 2B_{s1}K_{stf}((X_{b1} - X_{w1}) - (X_{b3} - X_{w3})) \quad (22)$$

$$T_{str} = 2B_{s2}K_{str}((X_{b2} - X_{w2}) - (X_{b4} - X_{w4})) \quad (23)$$

with $i = 1, 2, 3, 4$ and $j = 1, 2, 3$

Semi-Active Damper

The damper of the semi-active suspension system used in this study can be controlled continuously between upper and lower limits of the Force-Velocity characteristic curves. Therefore, it is theoretically capable of tracking a damping force demand independently of the damper velocity. The demanded damper force F_{sci} is generated by the controller according to different control laws and strategies. 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 [6]. Therefore, an additional control law is required to keep the control force in the controllable damper limits. In this study, the Rule Optimized Fuzzy Logic controller is used to generate the demanded suspension control force F_{sci} . The additional control law defined in Equation 24 is used to keep the actual semi-active damper force F_{svi} always within the allowable force limits of the damper.

$$F_{svi} = \begin{cases} F_{mini} & \text{if } F_{sci} < F_{mini} \\ F_{maxi} & \text{if } F_{sci} > F_{maxi} \\ F_{sci} & \text{if } F_{min} < F_{sci} < F_{maxi} \end{cases} \quad (24)$$

CONTROLLER DESIGN

In this research study, the Fuzzy Logic control theory is used to design a semi-active suspension controller. The Fuzzy Logic, which is one of the most intelligent control methods, offers several unique features that make it a particularly good choice for many control problems. It can be used to control nonlinear systems that 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 fails. 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 [14, 15, 17].

In order to design a FLC for the semi-active suspension system, certain assumptions are required to make the design process of the controller easier. As the system is quasi symmetrical, it is assumed that the symmetrical membership functions about the y-axis will provide a valid controller. Furthermore, a symmetrical rule-base and other constraints are also introduced as follows:

1. The universes of discourses are normalized to lie between -1 and 1 with scaling factors external to the FLC used to give appropriate values to the variables.

2. The first and last membership functions have their apexes at -1 and 1 respectively. This can be justified by the fact that changing the external scaling would have similar effect to changing these positions.

3. The membership functions and the rule-base of the FLC for the front and rear axles are the same, but the scaling factors for the inputs and outputs are different.

4. The number of fuzzy sets is constrained to be an odd integer greater than unity. In combination with the symmetry requirement, this means that the central membership function for all variables will have its apex at zero.

5. The base vertices of membership functions are coincident with the apex of the adjacent membership functions. This ensures that the value of any input variable is a member of at most two fuzzy sets, which is an intuitively sensible situation. It also ensures that when a variable's membership of any set is certain, i.e. unity, it is a member of no other sets [17].

6. The rule base and interface engine are based on the Mamdani-Type of fuzzy inference, and the center of area method is used for the defuzzification process.

7. The controller uses the body vertical velocity and acceleration at each corner as the input and generates the demanded damper force F_{sci} as the output.

As already mentioned before, the rule base, membership functions and the scaling factors of the FLC developed in this study have been obtained through an optimization process. As the GA is a reliable and robust method for searching solution spaces [18,19,20], it is used to optimize the proposed semi-active suspension controller. The GA can be performed using either binary or real valued encodings. With binary encoding, each parameter is converted into a binary string. These strings are concatenated and the genetic operations are performed on this concatenated string. With real-valued encoding, the parameters are kept in their real number format. Both forms of encodings are used in practice. The advantage of using a binary format is that it maximizes the number of hyperplane partitions directly available in the encoding for