

Preview Enhanced Rule-Optimized Fuzzy Logic Damper Controller

Mina Kaldas, Kemal Caliskan, Roman Henze, and Ferit Küçükay
IAE, TU Braunschweig

ABSTRACT

New developments in road profile measurement systems and in semi-active damper technology promote the application of preview control strategies to vehicle suspension systems. This paper details a new semi-active suspension control approach in which a rule-optimized Fuzzy Logic controller is enhanced through preview capability. The proposed approach utilizes an optimization process for obtaining the optimum membership functions and the optimum rule-base of the preview enhanced Fuzzy Logic controller. The preview enhanced Fuzzy Logic controller uses the feedforward road input information and the feedback vehicle state information as the controller inputs. An eleven degree of freedom full vehicle model, which is validated through laboratory tests performed on a hydraulic four-poster shaker, is used for the controller synthesis. The cost function including both ride comfort and road holding performance of the full vehicle is minimized through a discrete optimization process utilizing Genetic Algorithm (GA). The preview distance is also considered as a design parameter during the optimization process. The performance of the preview enhanced rule-optimized Fuzzy Logic controller is evaluated by using a measured stochastic road profile as vehicle model input. The results demonstrate the potential of the preview enhanced controller in improving all aspects of system performance compared to the rule-optimized Fuzzy Logic controller without preview.

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INTRODUCTION

Semi-active suspension systems are used to provide solutions that overcome the ride performance limitations of passive suspension systems while avoiding high system cost and energy consumption of fully active suspension systems. Some hardware and the control equipments of active suspension systems are also required by semi-active systems. However, the actuator and its complementary systems, e.g. hydraulic pumps and accumulators, are replaced with controllable dampers. Therefore, compared to the active systems, semi-active systems can clearly offer cheaper suspension control solutions with lower power demand. However, this is achieved at the expense of reduced ride comfort. The objective that attracts the current research studies is to improve the performance of semi-active control systems through different control approaches [1, 2, 3, 4, 5].

A wide variety of semi-active suspension systems have been investigated theoretically and experimentally using different types of control methods. Karnopp et al. [1] 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] modified the skyhook strategy by combining it with the 'groundhook' strategy to improve road holding performance parallel to the ride comfort. Soliman and Crolla [3] proposed a

self-tuning Linear Quadratic Regulator (LQR) control algorithm for a switchable damper suspension system, which provides significant improvement over a fixed gain LQR control algorithm and a passive 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. Kaldas et al. [4] developed a semi-active suspension system controller using an adaptive Fuzzy Logic algorithm together with a Kalman Filter for bounce velocity estimation. 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. The simulation results demonstrate the superiority of this control scheme to the optimal semi-active LQR controller and to the optimal passive system in terms of ride comfort and road holding on different road profiles.

In order to overcome the difficulties in the logic design and optimization of the Fuzzy Logic controllers for semi-active suspension systems, Kaldas et al. [5] developed an automatic design procedure for Fuzzy Logic damper controller based on Binary-Discrete GA. The key advantage of combining GA and Fuzzy Logic is that almost all the tasks of Fuzzy controller design can be accomplished automatically. The parameters of

Fuzzy Logic inference rules and membership functions are tuned by the optimizer to handle the conflicting requirements of ride comfort, road holding and suspension deflection.

The developments in road profile preview systems and semi-active damper technology promote the application of preview control strategies to vehicle suspension systems. Soliman and Crolla [6] used a LQR controller with look-ahead road preview input for a quarter vehicle semi-active suspension system. 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. It is 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. Kim and Yoon [7] proposed a control law for a semi-active suspension with preview control for the purpose of ride quality improvement, which is determined by reproducing the control force of an optimally controlled active suspension while suppressing its damping coefficient variation. The performance index of the optimal control for the active suspension is modified to include frequency-shaping by use of Parseval's theorem, which allows deemphasizing the effects of particular variables over specific frequency bands. Through the numerical simulations, it is found that the semi-active suspension may reduce the vertical acceleration of the driver's seat and the sprung mass motions significantly. The road-holding and tyre deflections were not affected much.

Muijderland et al. [8] developed active and semi-active suspension controllers with preview for the rear axle of a commercial vehicle. The active control is used to determine the 'ideal' performance of a linear system with a quadratic performance index, and this performance is considered as the control objective. The application of this concept is not restricted to the active control, but used for the semi-active system as well. The most promising control methods; DCC (Direct Calculation Controller), BBC (Branch and Bound Controller) and SQPC (Sequential Quadratic Programming Controller) are implemented in a test vehicle employing semi-active shock absorbers. The simulation and experimental results show that the preview concept is promising and it can give substantial improvement of the system performance, in particular for the active suspension but also for the semi-active one.

Gopala Rao and Narayanan [9] studied the performance of the look-ahead preview control of the semi-active suspension by using a four degree-of-freedom (DoF) half-car model traversing a random road profile with constant velocity. The optimal suspension is designed using the optimal control law which is derived by minimizing the weighted sum of the front and rear tyre deflections, suspension strokes and control forces. The simulation results indicate that, the overall performance of the vehicle is improved with preview control compared to the

performance without preview control. However, the performance improvement saturates beyond a preview distance. Seong et al [10] used also the optimal preview control for a vehicle featuring MR shock absorbers. A commercial MR shock absorber, Delphi Magneride(TM), which is applicable to high class passenger vehicles, is adopted and its field dependent damping force and dynamic responses are experimentally evaluated. The governing equations of motion for the full-vehicle model are integrated with the MR shock absorber model and the optimal controller with preview control algorithm. The simulations with random road profile inputs demonstrate that the proposed optimal preview control algorithm can provide much better vibration control performance compared with the conventional optimal control algorithm.

In this study, a new semi-active suspension control approach is constituted by enhancing a rule-optimized Fuzzy Logic controller [5] through preview capability. The controller synthesis is performed through an optimization process which determines the optimum membership functions and the optimum rule-base of the preview enhanced Fuzzy Logic controller. The proposed Fuzzy Logic control scheme with preview tunes the suspension damper continuously to handle the conflicting requirements of ride comfort, road holding and suspension deflection. An experimentally verified full vehicle ride dynamics model and a measured stochastic road profile are used for evaluating the performance of the proposed preview enhanced Rule-Optimized Fuzzy Logic controller.

VEHICLE MATHEMATICAL MODEL

In this study, a generic full vehicle suspension model with nonlinear 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 at each corner is modeled using a nonlinear spring and a viscous damper in series with a rubber top mount. The nonlinear characteristics of the damper are taken into account by using the non-linear Force-Velocity damper characteristics together with a first order time delay model. A detailed and experimentally verified damper top mount model has been employed inside the model [11]. The inertial forces at the dampers and the top mounts are neglected. The tyre is modeled with a non-parametric Force-Displacement-Velocity map and point contact is assumed between the tyres and pre-filtered road profile. Tyre-road separation and tire is taken into account. 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 freedom only, and it is modeled as a mass

supported by a linear spring and a linear damper. The axis 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:

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

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

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

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

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

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

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

The equation of motion for the driver seat can be written as:

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

The bounce motion of the wheels is modeled as:

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

where;

$$Z_{b1} = Z_b - L_1 \theta_b + B_{s1} \phi_b \quad (9.a)$$

$$Z_{b2} = Z_b + L_2 \theta_b + B_{s2} \phi_b \quad (9.b)$$

$$Z_{b3} = Z_b - L_1 \theta_b - B_{s1} \phi_b \quad (9.c)$$

$$Z_{b4} = Z_b + L_2 \theta_b - B_{s2} \phi_b \quad (9.d)$$

$$Z_{e1} = Z_e - L_{e1} \theta_e + B_{e1} \phi_e \quad (10.a)$$

$$Z_{e2} = Z_e - L_{e2} \theta_e - B_{e2} \phi_e \quad (10.b)$$

$$Z_{e3} = Z_e + L_{e3} \theta_e - B_{e3} \phi_e \quad (10.c)$$

$$Z_{be1} = Z_b - L_{be1} \theta_b + B_{be1} \phi_b \quad (11.a)$$

$$Z_{be2} = Z_b - L_{be2} \theta_b - B_{be2} \phi_b \quad (11.b)$$

$$Z_{be3} = Z_b - L_{be3} \theta_b - B_{be3} \phi_b \quad (11.c)$$

$$Z_{bs} = Z_b - L_{bs} \theta_b + B_{bs} \phi_b \quad (12)$$

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

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

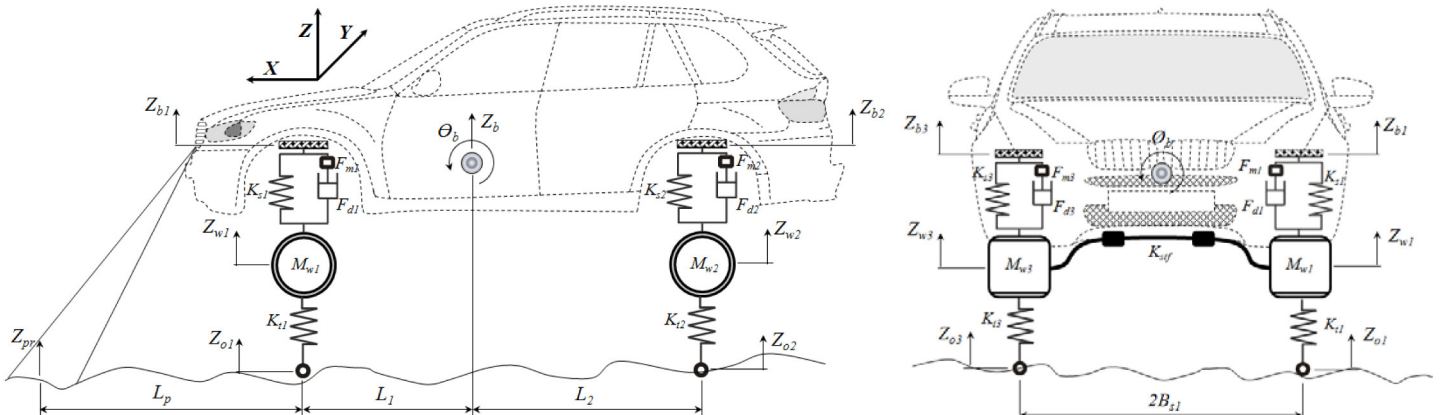


Figure 1. Full vehicle model.

$$F_s = K_s(Z_s - Z_{bs}) + C_s(\dot{Z}_s - \dot{Z}_{bs}) \quad (15)$$

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

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

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

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

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

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

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

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

with $i = 1, 2, 3, 4$ (front left, rear left, front right and rear right body corners) and $j = 1, 2, 3$ (transmission mount, engine mount, and subfram mount)

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 [12]. Therefore, an additional control law is required to keep the control force in the controllable damper limits. In this study, the Preview enhanced Rule Optimized Fuzzy Logic controller is used to generate the overall 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.

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

CONTROLLER DESIGN

The Fuzzy Logic is one of the most intelligent control methods, which 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 controller 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 [13, 14, 15].

In order to design a rule optimized FLC for the semi-active suspension system; certain assumptions are required for simplifying the controller design process. As the system is quasi symmetrical, it is assumed that the symmetrical membership functions about the y-axis will provide a valid controller [5]. 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 external scaling factors 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.
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_{sai} as the output.

More details about the rule-optimized Fuzzy Logic controller design can be found in Kaldas et al. [5]. The rule-optimized Fuzzy Logic controller is extended by assuming that the road inputs $z_{o1,3}$ for $[t, t+t_p]$ can be detected by a preview sensor located at the front of the vehicle. That is, the preview information about the ground excitation $z_o(t+t_p)$ at $t+t_p$ of current time (t) is available. In addition, the rear wheels