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A New Adaptive Fuzzy-Hybrid Control Strategy of Semi-Active Suspension with Magneto-Rheological Damper

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Abstract
This paper presents the design and analysis of a new adaptive fuzzy (AF) logic and hybrid (skyhook plus groundhook) control technique applied to a semi-active suspension system of a quarter car mode. The hybrid control is applied because of its very good performance in ride comfort and road handling. Meanwhile, Fuzzy adaptive system is suitable for analysis of stability with non-linear performances. The adaptive fuzzy algorithm is used to approximate the estimated mass of the variable damping in the Hybrid loop. This model is adopting a Takagi-Sugeno configuration with a back propagation learning method typically used in a neural network configuration, which uses a product inference engine, singleton fuzzifier, centre average defuzzifier, and Gaussian membership function. Numerical simulations were conducted based on Simulink/Matlab using Fuzzy Logic Toolbox. It is found that the semi-active suspension system with the proposed adaptive fuzzy-hybrid yields superior performance compared to both the Hybrid and the Passive counterparts.

Keywords: MR damper, Fuzzy-hybrid control, semi-active suspension, numerical simulation

Introduction

Passive suspensions are commonly used in vehicles. These systems generally consist of springs and dampers with fixed properties (Tsampardoukas, 2008). To get better handling and ride comfort characteristics simultaneously, the use of active and semi-active suspension systems has become a recent focus area in automotive industries. Active systems can supply and dissipate energy to/from a system. There is a force actuator that can provide necessary force to the system. The response of the system can be adjusted according to road inputs. The main disadvantage is the high power demand from the vehicle power sources. Semi-active systems are a compromise between the active and passive systems (Nguyen and Choi, 2009; Yao, et al. 2002). Basically, semi-active suspensions have four types, i.e. controllable friction devices, variable orifice dampers, electrorheological (ER) fluid dampers, and magnetorheological (MR) fluid dampers (Tsampardoukas, 2008). MR and ER semi-active dampers are fluid dampers which change their viscosity according to the magnetic or electric field supplied to the system. Recently, MR dampers have become the search focus for semi-active dampers, since their available damping range and the response time are almost as good as active dampers in spite of the lower power requirement, especially about control strategies of MR Damper (Choi and Wereley, 2003; Li et al., 2000; Lee and Choi, 2000; Wang and Gordaninejad, 2007).

Several semi-active control strategies have been proposed and investigated since Karnopp (1973) developed the Skyhook control strategy to improve comfort but is limited to improve road holding. Skyhook control was also developed by Nguyen and Choi (2009), which improves both ride quality and road holding ability by the Linear Quadratic Regulator control using a minimum norm criterion. To overcome the limitation of skyhook control in depressing the vibration of car suspension, other researchers discovered the groundhook control and hybrid control. The hybrid control approach was a combination of a skyhook control approach and a groundhook control law. Ahmadian and Vahdati (2006) and Felix-Herran, et al (2008) studied this control policy. Their results show that skyhook control is much more effective in improving the ride comfort, while the groundhook control is effective in achieving better road holding ability and improving vehicle stability. Thus, the hybrid control is a tradeoff between the skyhook control and the groundhook control.
Nowadays, many control strategies based on Fuzzy Logic Control were developed by the researchers. Biglarbegian et al (2008) proposed a Neuro Fuzzy (NF) control strategy for a quarter-car model and conducted experimental evaluation with a Semi Active Suspension System (SASS). Tusset et al (2009) studied control strategies of nonlinear vehicle suspension using MR damper. Khajavi and Abdollahi (2007) concerned a proposed Fuzzy Logic semi active suspension system designed for specific automobile with passive suspension system. Li and Zhao (2010) also proposed a Fuzzy Controller with Fuzzy Rules which were evaluated using the Matlab Fuzzy logic control toolbox. Felix-Herran et al (2010) presented a Takagi-Sugeno (T-S) fuzzy model for a analysis of a quarter-car semi-active suspension with an MR damper. Rashid et al (2011) developed a hybrid Fuzzy Logic plus proportional–integral–derivative (PID) controller for analysis of a similar quarter-car model. The results indicated that the body vertical acceleration is reduced obviously by way of using fuzzy control on semi-active suspension, meanwhile, the vehicle ride comfort and handling stability is improved.
The assessment of overall good control performances of semi-active suspensions is generally based on three criteria: road handling, ride comfort, and stability. It is noted that most of studies or control algorithms can only achieve better performances in one or two criteria, which has a certain limitation to improve the vehicle overall performances. Thus, it is crucial to develop advanced control strategies to well improve overall performances of semi-active suspensions. This is the major motivation of our work. In this work, we developed a new control strategy aiming to improve ride comfort, road handling and vehicle stability simultaneously. This new strategy is a combination of both an Adaptive Fuzzy Logic and a Hybrid Controllers, where the adaptive fuzzy logic model is adopting a Takagi-Sugeno configuration with a back propagation learning method typically used in a neural network configuration. The network uses a product inference engine, singleton fuzzifier, centre average defuzzifier, and Gaussian membership function. Performance of the suspension system is validated and evaluated by means numerical simulation using Matlab/SIMULINK Fuzzy Logic Toolbox in terms of the following parameter: the sprung mass acceleration sprung mass displacement, suspension deflection and tyre acceleration.

MR Damper Model

One model that is numerically tractable and has been used extensively for modeling hysteretic systems is the Bouc-Wen model. The Bouc-Wen model is extremely versatile and can exhibit a wide variety of hysteretic behavior. To better predict the damper response in this region, a modified version of the system is proposed by Spencer (1996), as shown in Fig. 1. To obtain the governing equations for this model, consider only the upper section of the model. The forces on either side of the rigid bar are equivalent; therefore,

$$c_1\dot{y} = \propto z + k_0(x-y) + c_0(\dot{x}-\dot{y}) \tag{1}$$

where the evolutionary variable *z* is governed by

$$\dot{z} = -\gamma|\dot{x}-\dot{y}|z|z|^{n-1} - \beta(\dot{x}-\dot{y})|z|^n + A(\dot{x}-\dot{y}) \quad (2)$$

Solving for $\dot{y}$ results in

$$\dot{y} = \frac{1}{c_1+c_2} c_0\dot{x} + k_0(x-x_0) + \propto z \quad (3)$$

The total force generated by the system is then found by summing the forces in the upper and lower sections of the system in Fig. 1 below.

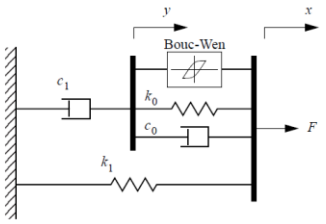

Figure 1. Proposed Mechanical Model of the MR Damper

$$F = \propto z + k_0(x-y) + c_0(\dot{x}-\dot{y}) + k_1(x-x_0) \quad (4)$$

Total force can also be written as

$$F = c_1\dot{y} + k_1(x-x_0) \quad (5)$$

In this model, the accumulator stiffness is represented by k1 and the viscous damping observed at larger velocities is represented by c0. A dashpot, represented by c1, is included in the model to produce the roll-off that was observed in the experimental data at low velocities, k0 is present to control the stiffness at large velocities, and x0 is the initial displacement of spring k1 associated with the nominal damper force due to the accumulator.

Dynamic Analysis of Vehicle Model

For simplicity, a quarter-care model, as shown in Figure 2, is used for simulation analysis. The motion of equations are:

$$m_s\ddot{x}_2 + c_s(\dot{x}_2-\dot{x}_1) + k_s(x_2-x_1) = 0 \quad (6)$$

$$m_u\ddot{x}_1 + k_t(x_1-x_{in}) + c_s(\dot{x}_1-\dot{x}_2) + k_s(x_1-x_2) = 0 \quad (7)$$

In this equation, m_u represents a wheel vehicle mass (unsprung mass), and k_t is the tire stiffness. In addition, x_2 is the sprung mass displacement, and *x1* represents the unsprung mass displacement.
Replacing $c_s(\dot{x}_2-\dot{x}_1)$ by F_d:

$$m_s\ddot{x}_2 + F_d + k_s(x_2-x_1) = 0 \quad (8a)$$

$$m_u\ddot{x}_1 + k_t(x_1-x_{in}) - F_d + k_s(x_1-x_2) = 0 \quad (8b)$$

From Force MR Damper Modified Bauc Wen Model equation:

$$F_d = \propto z + k_0(x_2-y) + c_0(\dot{x}_2-\dot{y}) + k_1(x_2-x_1)\,; \quad \text{or} \quad (9)$$

$$F_d = c_1\dot{y} + k_1(x_2-x_1) \quad (10)$$

$$\dot{y} = \frac{1}{c_1+c_2} c_0\dot{x}_2 + k_0(x_2-x_1) + \propto z \quad (11)$$

Two equations of motion are obtained.

$$m_s\ddot{x}_2 = -\propto z - k_0(x_2-y) - c_0(\dot{x}_2-\dot{y}) - (k_1+k_s)(x_2-x_1) \quad (12)$$

$$m_u\ddot{x}_1 = -k_t(x_1-x_{in}) - c_1\dot{y} - (k_1+k_s)(x_1-x_2) \quad (13)$$

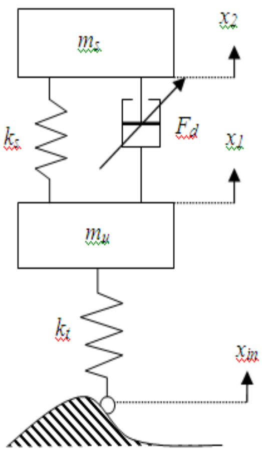

Figure 2. Two DOF Quarter Car Model

Adaptive Fuzzy Logic-Hybrid Control Scheme

Adaptive fuzzy logic control can change and adjust the control parameters automatically according to the desired system behavior (Wang, 1994). Adaptive fuzzy system can be viewed as a system that has an ability to generate the rules automatically through learning. Conventional fuzzy logic control involves four components or operations method for fuzzification, membership function, method for fuzzy inference and method for defuzzification. An adaptive fuzzy logic network model adopting a Takagi-Sugeno configuration is adopted in this study. It incorporates a back propagation learning method typically used in a neural network configuration. The adaptive fuzzy system is shown in Figure 3. In this network, the structure will be determined during the initialisation stage and all fuzzy membership functions are connected to form completed rules. The network uses a product inference engine, singleton fuzzifier, centre average defuzzifier, and Gaussian membership function (Wang, 1994):

$$f(x) = \frac{\sum_{l=1}^{M} y^{-l}\left[\prod_{i=1}^{N} a_i^l exp\left(-\left(\frac{x_i - x_i^{-l}}{\sigma_i^l}\right)^2\right)\right]}{\sum_{l=1}^{M}\left[\prod_{i=1}^{N} a_i^l exp\left(-\left(\frac{x_i - x_i^{-l}}{\sigma_i^l}\right)^2\right)\right]} \quad (14)$$

where x_i is input to the fuzzy network, i =1,..., n (n is number of inputs) and *l* =1,..., M (M is the number of rules and N is the number of inputs while f (x) is the signal output fuzzy network). The parameter y^{-l} is the centre of *l*-th consequent fuzzy set and x_i^{-l} and σ^l_i are centre and width of Gaussian antecedent membership functions at rule *l* and input *i*, respectively. By assuming $a_i^{\,l} = 1$, the error system can be expressed as:

$$e^p = v(x) = \frac{1}{2}\{f_{desired}(x^p) - f_{actual}(x^p)\}^2 \quad (15)$$

The update of x is given by:

$$x(k+1) = x(k) + \Delta x \quad (16a)$$

$$\Delta x = -\alpha \frac{\partial e^P}{\partial x}\bigg|_k \quad (16b)$$

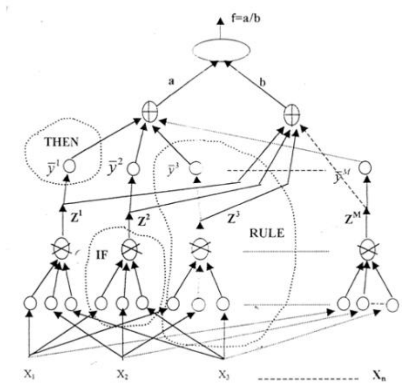

Figure 3. An Adaptive Fuzzy Network (Wang, 1994)

Where α is the learning rate. In order to minimize *v (x)* in equation (15) with respect to the parameter *x*, the updates of the parameters $\bar{y}^l, \bar{x}^l, \sigma_i^l$ are defined as:

$$\bar{y}^l(k+1) = \bar{y}^l\,(k) - \alpha\frac{(f-d)}{b} z^l \tag{17}$$

$$\bar{x}_i{}^l(k+1) = \bar{x}_i{}^l\,(k) - \alpha\frac{(f-d)}{b}(\bar{y}^l(k)-f) z^l \frac{2(x_i-\bar{x}_i{}^l\,(k))}{\bar{x}_i{}^l\,(k)^2} \tag{18}$$

$$\bar{\sigma}_i{}^l(k+1) = \bar{\sigma}_i{}^l\,(k) - \alpha\frac{(f-d)}{b}(\bar{y}^l(k)-f) z^l \frac{2(x_i-\bar{x}_i{}^l\,(k))}{\bar{x}_i{}^l\,(k)^3} \tag{19}$$

And

$$f = f_{actual}\,(x)^P, d = f_{desired}\,(x)^P, z^l = \prod_{i=1}^{N} exp\left(-\left(\frac{x_i - x_i{}^l}{\sigma_i^l}\right)^2\right),$$

$$a = \sum_{l=1}^{M}(\bar{y}^l\, z^l),$$

$$b = \sum_{l=1}^{M}(\, z^l).$$

where *a* is the result defuzzification, *b* is the number of membership functions and the *z* value is the value of membership function of *x*.

Adaptive Fuzzy Hybrid Controller Design

The semi-active damping control concept is illustrated in Figure 4. The vehicle model has force inputs from MR dampers and disturbance inputs from the road surface profile. The controller determines required damper forces needed for a chosen control strategy. The MR dampers should then be actuated by proper currents that will generate the MR damping force inputs determined by the controller. After required currents are calculated, MR dampers are actuated by these. In this work, the currents to provide the desired damping forces are assumed to be correctly determined as long as the forces are in the feasible damping range.

The adaptive fuzzy (AF) hybrid controller was designed to satisfy performance requirements using Takagi-Sugeno AF model. The training algorithm used for adaptive fuzzy logic is a back-propagation real time learning method (equation 16). The input and output universes of discourse of the fuzzy controller are normalized in the range [-1,1]. Two inputs of the adaptive fuzzy logic controller are error *e* and change of error *de*. These two inputs are scaled by two gain coefficients K_e and K_{de} respectively, so as to normalize these inputs in the range [-1,1]. The output is the force ranging from -2000 to 2000 N and is considered a singleton value scaled by K_{01} normalized in the range [-1,1]. Note that the numerical scale K_e, K_{de} and K_{01} were acquired prior to simulation based on human experience and also results from previous studies that employs conventional methods.

Figure 5 shows a representation of the membership functions for respective parameters noting that N denotes ‘negative’, Z is ‘zero’ and P is ‘positive’.

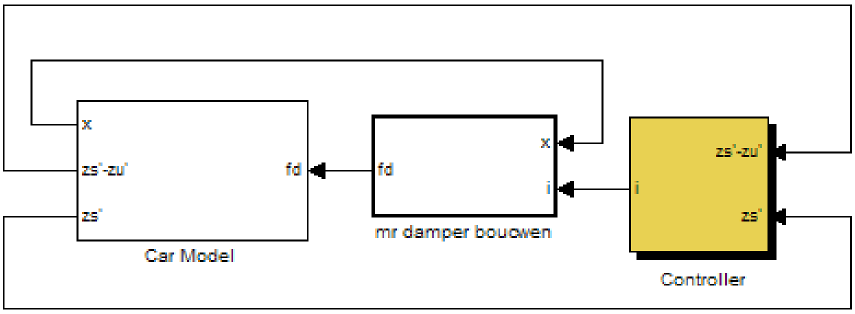

Figure 4. Semi Active Vehicle Suspension Control Design in Simulink Diagram

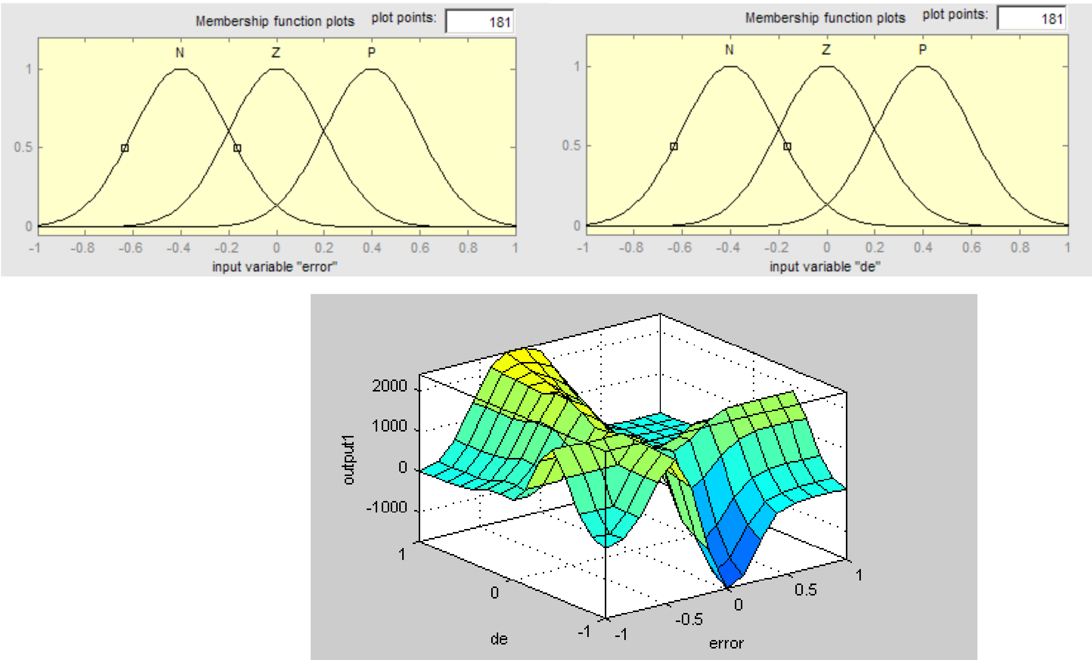

Figure 5. Membership functions for the input/output parameters of AF

Simulation Results and Discussion

The parameters of the quarter car model and hydraulic actuator are obtained from the reference (Dong, 2010) and listed as follows:

k_s = 60000 N/m, k_t = 181000 N/m, m_u = 60.4 kg, m_s = 424.5 kg, c_s = 1000 Ns/m, α equals 0.8, G_{sky} = 2840 Ns/m and G_{ground} = 3280 Ns/m.

Simulation was performed using Fuzzy Logic Toolbox of Simulink/Matlab. The system dynamic has the road disturbance inputs. It also has four outputs which are the body displacement, suspension deflection, tyre deflection and body acceleration which serve as the main parameters of interest or responses to be analysed and evaluated for the dynamic performance of the suspension system. Simulation is performed using the parameters and conditions as described in the earlier part of this section. Three types of control systems are compared and evaluated, namely Passive, Hybrid and AF-Hybrid schemes. All the relevant parameters and conditions are maintained the same for all the schemes to ensure a realistic and fair one-to-one comparison. It is generally considered an enhancement in system performance in terms of vehicle riding comfort, road handling and stability if all the curves show reduction in the amplitudes.

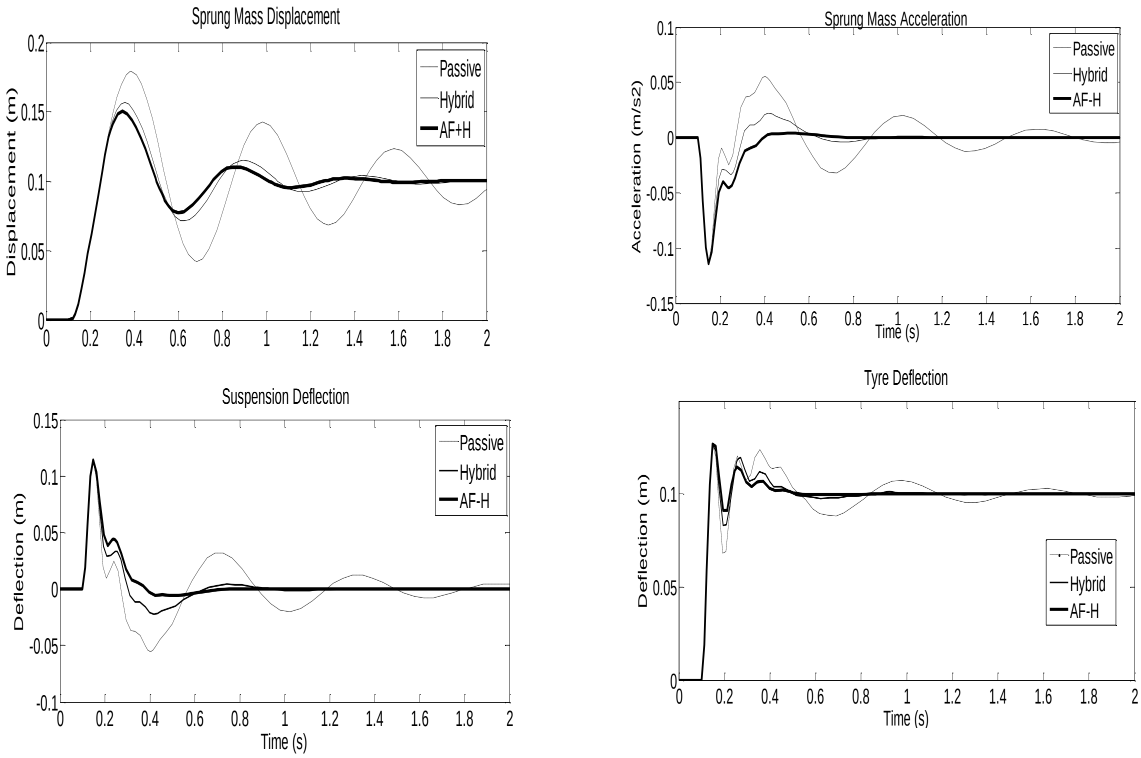

Figure 7. Graphics Responses under Step Input

Figure 7 a-d shows responses of the system with step function disturbance. Figure 7a shows the curve for sprung mass displacement for all the three schemes. In addition, the semi-active suspension with skyhook control can also achieve a slightly smaller peak-to-peak displacement than the hybrid and passive case. Those reductions compared to the passive and hybrid control suspension system show that the semi-active suspension system using the adaptive fuzzy-hybrid control could improve the ride comfort under road step function.

Figure 7b obtained with the hybrid controller show that this algorithm is capable of reducing the first peak-to-peak value of the suspension deflection and shortening the adjusting time over the results of the passive case. The adaptive fuzzy-hybrid control did an excellent job in reducing the sprung mass displacement and suspension deflection than Hybrid controller and passive suspension systems. Figure 7c illustrates the trend in the sprung mass acceleration, while Figure 7d exhibits the tyre deflection. Compared with other control algorithms, the proposed AF-hybrid control strategy has the best improvement in reduction of the sprung mass acceleration. When the frequency of the sinusoidal excitation approaches the sprung mass resonance frequency, the semi-active suspension via adaptive fuzzy-hybrid control can reduce the acceleration amplitude of the sprung mass vibration.

When comparing to the other two algorithms, it can be found that the improvement in ride comfort is inferior to the other four algorithms and the improvement in stability is superior to the cases with the other algorithms. This may be due to the fact that the design principle of this algorithm is based on the weighting between the skyhook control and the groundhook control. A suitable weighting factor for various road conditions is difficult to determine and needs further efforts in the future. Similar to the hybrid control algorithm, the formulation of adaptive fuzzy logic control algorithm is also based on the skyhook control principle and the groundhook control principle.

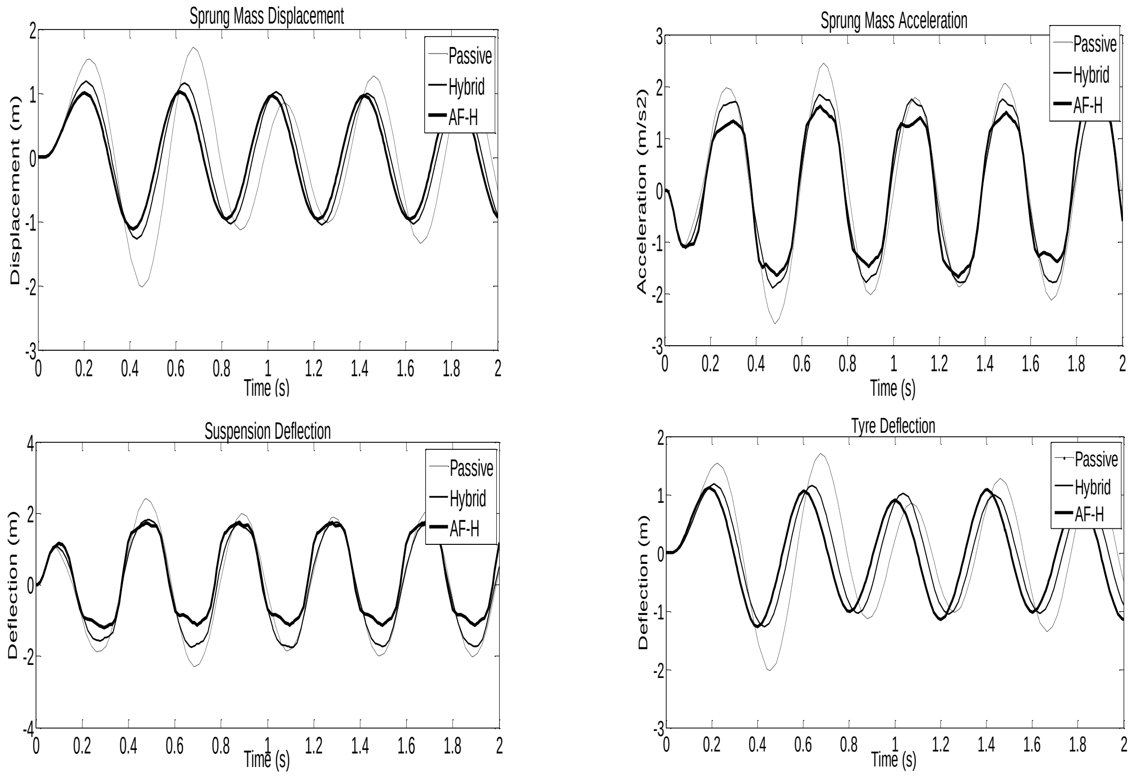

Figure 8. Graphics Responses under Sinusoidal Input

Therefore, its control performance has some similar characteristics to skyhook control and hybrid control. For the step input or sinusoidal input, the semi-active suspension system with fuzzy logic control has slightly bigger first peak-to-peak value of vertical acceleration and a shorter adjusting time than the skyhook control, which shows that a better improvement in alleviating the strong discomfort caused by the step or bump road input than the skyhook control. For the random road input, the MR suspension with the fuzzy logic control can effectively depress the first resonance frequency and reduce the RMS of acceleration of the sprung masses without deteriorating the vibration of the unsprung masses.

Figures 8 a-d show the responses of system with sinusoidal disturbance. Similar to the step input disturbance, the performance of the system clearly indicates the superiority of the adaptive fuzzy-hybrid control scheme over its counterparts in accommodating the introduced conditions. The magnitude of compensation is much greater than that of the step input. This further reaffirms the robustness and effectiveness of the proposed scheme in controlling the vertical motion of the suspension system. Thus, it is expected that the new scheme could greatly contribute to the improvement of the vehicle riding comfort performance.

Conclusion

This paper presented a simulation study using Matlab/Simulink of new adaptive fuzzy-hybrid controllers, to control the semi active suspension control system. This adaptive fuzzy logic model is adopting a Takagi-Sugeno configuration with a back propagation learning method typically used in a neural network configuration. The simulations results have shown that the adaptive fuzzy-hybrid controller can suppress the worst case step and sinusoidal function road disturbances effectively, and hence, it would be able to handle other less severe real road situations better than the conventional controllers. This paper is quite appropriate in justifying that the semi active MR damper suspension system can be effectively extended and constructed from the pilot plant scale to the passenger vehicle with improved ride comfort, road handling and stability using adaptive fuzzy-hybrid controllers. An on-going project via the development of a full working prototype is underway to practically verify and validate the simulation trends of the parameters of interest.

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