Research Article

Design of a Road Friendly SAS System for Heavy-Duty Vehicles Based on a Fuzzy-Hybrid-ADD and GH-Control Strategy

Jing Zhao, Pak Kin Wong, Zhengchao Xie, Xinbo Ma, and Caiyang Wei

Department of Electromechanical Engineering, University of Macau, Macau

Correspondence should be addressed to Zhengchao Xie; zxie@umac.mo

Semiactive suspension (SAS) system has been widely used for its outstanding performance in offering competent ride quality, road holding, and handling capacity. However, the road friendliness is also one of the crucial factors that should be attached in the design of the SAS system for heavy-duty vehicles. In this study, a fuzzy controlled hybrid-acceleration driven damper (ADD) and ground hook- (GH-) control strategy is proposed for SAS system of heavy-duty vehicles. Firstly, a quarter-vehicle model with SAS system is constructed. Then, aiming to improve the ride quality and road friendliness, a hybrid-ADD and GH-control strategy is proposed under the coordination of the fuzzy controller. Numerical results show that the ride quality and road friendliness of the SAS system with the proposed control strategy outperform those with traditional hybrid-sky hook and ground hook-control strategy. It is also verified that the proposed strategy is superior to the sole ADD approach and sole ground hook approach in improving the vehicle overall performance.

1. Introduction

In the past decades, ever increasing requirement in commercial transportation inevitably accelerates the maintenance cycle of the road (e.g., frequently overloading of the building materials in commercial vehicles accelerates the rate of pavement damage) [1]. However, regarding the probability of road damage coming from commercial vehicles, the heavy-duty vehicle accounts for a large percentage and is responsible for most of the road damage due to its huge axle load. The heavy-duty vehicle has been prevalently used and it cannot be replaced in commercial transportations due to its high loading capacity and low freight rate. So, taking into account the cost of road maintenance, this work aims to design a road friendly suspension system for heavy-duty vehicles so that the road damage coming from heavy-duty vehicles can be reduced.

Road friendliness refers to the extent of damage exerted on the road by the vehicles, and it can be quantified by the dynamic tire load (DTL) of the vehicle. The design of the road friendly suspension system can be regarded as an effective method to improve the road friendliness of the vehicle.

A well-designed road friendly suspension should be capable of decreasing the DTL and minimizing the road damage coming from the vehicle. With respect to the vehicle DTL, it is commonly accepted that by adopting proper suspension system the vehicle DTL can be effectively declined.

As far as the suspension systems are concerned, the semiactive suspension (SAS) system has been considered as the most popular type for heavy-duty vehicles as it can provide an achievable performance between the active suspension system and passive suspension. Moreover, the low power consumption and fail-safe property of the SAS system also determine that it is applicable for heavy-duty vehicles. As a result, a SAS system is utilized in the design of the road friendly suspension system for heavy-duty vehicles.

In addition to the road friendliness, another concern worth mentioning for heavy-duty vehicles is the vertical acceleration. During the transportation, the goods in the rear part of heavy-duty vehicles probably suffer a fluctuation along with the sprung mass acceleration (SMA) of the vehicle, and this may lead to certain damage to the goods. To protect the goods from damaging, the SMA of heavy-duty vehicles should be minimized and stabilized within a certain range.

With the above considerations, the objective of this paper is to propose a SAS system for heavy-duty vehicles to reduce the DTL and SMA simultaneously. To accomplish this target, of great concern is the control strategy of the SAS system, because the performance of the SAS system is largely influenced by the control strategy applied in its dissipation device. For most of the heavy-duty vehicles, the dissipation device of the SAS system is an adjustable damper. Therefore, a suitable control strategy must be selected for the adjustable damper of the SAS system.

Various investigations have been done for the control strategies of the adjustable damper. To control the SMA, the most widely employed strategy is the sky hook (SH) approach, which is first proposed by Karnopp et al. [2]. The idea of the SH approach is to attach the vehicle chassis to the sky via an active damping force. By this way, the vibration from the vehicle chassis can be reduced accordingly. It has been verified by many studies as a simple but effective way to reduce the SMA [3–5]. In addition, another effective approach for SMA control is the acceleration-driven damper (ADD) control strategy [6, 7]. This approach has been proved to be the optimal one in the minimization of the SMA and also more simple in the aspect of implementation than the SH approach.

When it turns to the control of the vehicle DTL, some of the existing investigations are dedicated to the study of the opposite side of the SH approach, namely, ground hook (GH) approach [8, 9]. The GH approach focuses on increasing the suspension damping and reducing the DTL together. Furthermore, it is also reported that the H infinity control is also favorable for the control of the DTL [10]. However, when applying the H infinity control to the adjustable damper of the SAS system, a constraint should be set for the adjustable damper in advance and as well a saturation should also be considered for the damping force. The inaccuracy that comes from the constraint and complicated saturation setting make the H infinity approach popular in some active suspension system but the SAS system.

It should be noted that the single application of any of the above approaches cannot enable the well design of the SAS system (i.e., impossible to improve the SMA and the DTL simultaneously). So, the hybrid strategy, in which the individual control approaches are combined to achieve different potential targets, is proposed, such as hybrid optimal control and hybrid integrated control [11, 12]. Within the hybrid control strategy, a tuning method should be well defined for different individual control approaches and then a promising performance can be obtained. As far as the tuning method is concerned, the fuzzy logic control has been proved to be effective in the tradeoff of two different control objectives [13–15], and it is also employed in this work.

Up to this point, a fuzzy controlled hybrid-ADD and GH-control strategy is proposed for the SAS system. Moreover, a traditional hybrid-SH and GH-control which uses a straight-forward tuning method is also introduced as a comparative case so as to highlight the superiority of the proposed hybrid fuzzy tuning method. Furthermore, the sole ADD approach and the sole GH approach are also selected as the comparative cases. The rest of this paper is formatted as follows. Section 2
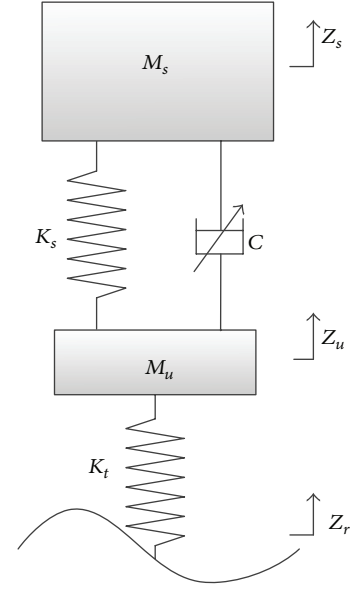

FIGURE 1: Quarter-vehicle model with semiactive suspension system.

introduces the modeling of the quarter vehicle. The presentation of the proposed control strategy and the comparative cases are illustrated in Section 3. Section 4 gives numerical results and analysis, and a conclusion is provided in Section 5.

2. Modeling

To examine the proposed control strategy, a vehicle model should be constructed first. Generally speaking, the rear suspension undertakes the main load of heavy-duty vehicles, so the goods damage as well as the road damage is often seriously found in the rear part of heavy-duty vehicles. In view of this point, the model of the rear suspension system is chosen to study proposed control strategy.

The objective of this work is to control the SMA and the DTL of heavy-duty vehicles, and 2 degrees of freedom (DOF) vehicle model is capable of examining the above control objectives. Therefore, a quarter-vehicle model is employed in this work. The schematic diagram of the quarter-vehicle model with SAS system is shown in Figure 1.

Moreover, it is also important to describe the equation of motions for the quarter-vehicle model so that the control input and output can be presented more clearly. For the quarter-vehicle model, the vehicle motions in vertical direction can be written as

$$M_s \ddot{Z}_s = C\left(\dot{Z}_u - \dot{Z}_s\right) + K_s\left(Z_u - Z_s\right),$$
$$M_u \ddot{Z}_u = C\left(\dot{Z}_s - \dot{Z}_u\right) + K_s\left(Z_s - Z_u\right) - K_t\left(Z_u - Z_r\right),$$

$$(1)$$

where m_s and m_u are the sprung mass and unsprung mass, respectively, k_t is the stiffness of the tire, k_s is the stiffness of the spring, C is the damping coefficient of the damper, Z_r is the road input, and Z_u and Z_s are the displacement of

TABLE 1: Parameters for modeling.

Item	Value	Unit
M_s	3257	Kg
M_u	312	Kg
K_s	3.5×10^5	KN/m
K_t	3×10^6	KN/m
$G(n_0)$	2.56×10^{-6}	/
f_0	72	Hz
v	20	m/s
$w(t)$	1	/
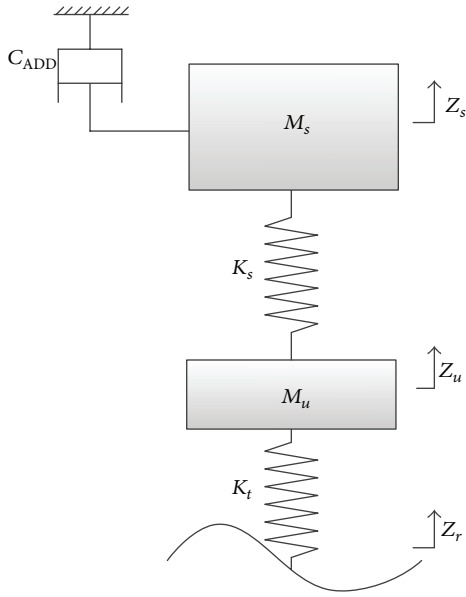
FIGURE 2: Quarter-vehicle SAS system model with ADD approach.

FIGURE 3: Quarter-vehicle SAS system with GH approach.

FIGURE 4: Road excitation.

the unsprung mass and displacement of the sprung mass, respectively.

By this means, the quarter-vehicle model with SAS system can be constructed with the parameters in Table 1. Also, the SAS system with ADD approach and GH approach is also created in the quarter-vehicle model, as shown in Figures 2 and 3, respectively.

To further conduct the numerical analysis, a road input should be provided as the excitation of the tire. In this connection, a band-limit white noise method is utilized as the power source of the road profile and a C-class level road pavement is chosen as the road excitation of the tire. The road input of the vehicle tire can be presented as

$$\dot{Z}_r(t) = -2\pi f_0 Z_r(t) + 2\pi \sqrt{G_0(n)\, v} w(t), \qquad (2)$$

where f_0 is the lower cut-off frequency, $G_0(n)$ is the road roughness coefficient, v is the vehicle speed, and $w(t)$ is the signal power of the white noise. Then, with the parameters in Table 1, the road excitation can be obtained, as shown in Figure 4.
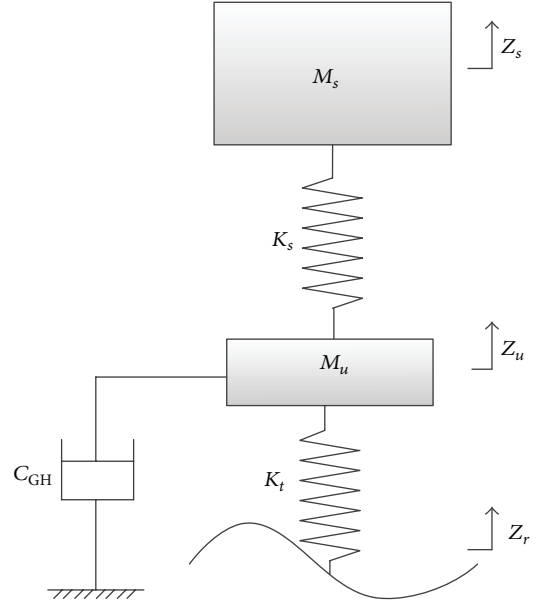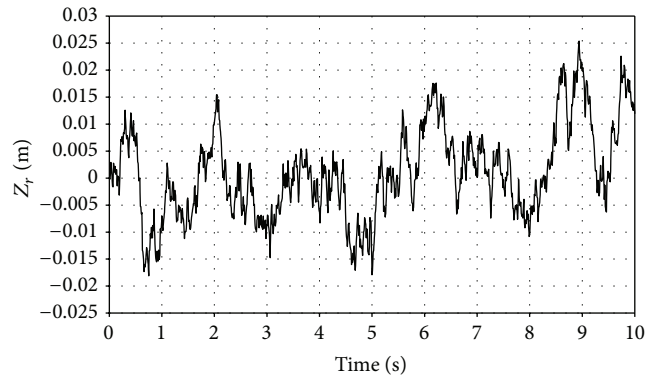
3. Control Strategies

This section describes the design process of the proposed control strategy. Also, to highlight the performance of the proposed control strategy, some comparative cases such as sole ADD approach, sole GH approach, and a straightforward tuning hybrid-SH and GH-control strategy are also introduced. Regarding the control of the SAS system, of particular concern is the control of the damping force. So, for each of the above cases, the control process regarding the damping force is discussed, as shown below.

Case 1 (ADD approach). The ADD approach is improved on the basis of the SH approach and it mainly focuses on the control of the SMA. The ADD approach takes the state of the sprung mass as its control variables and then switches the damping force with the various states of the sprung mass. The configuration of the ADD approach for the SAS system is shown in Figure 2.
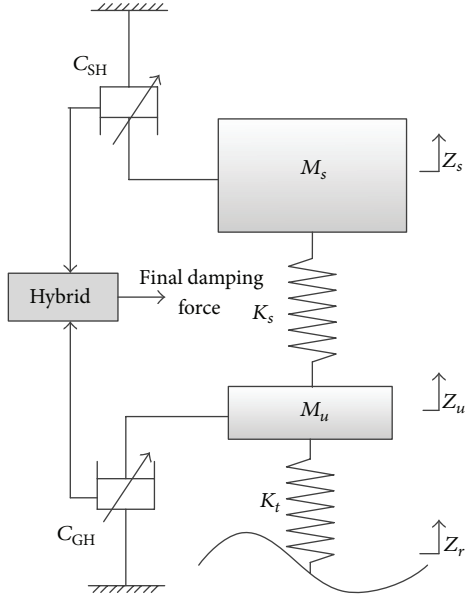
Figure 5: Quarter-vehicle SAS system model with hybrid-SH and GH-control.

Figure 6: Quarter-vehicle SAS system model with fuzzy-hybrid-ADD and GH-control.

The damping force of the SAS system with ADD approach can be represented as

$$F_{\text{ADD}} = \begin{cases} C_{\text{ADD}}\dot{Z}_s, & \text{when } \ddot{Z}_s\left(\dot{Z}_s - \dot{Z}_u\right) \geq 0 \\ 0, & \text{when } \ddot{Z}_s\left(\dot{Z}_s - \dot{Z}_u\right) < 0, \end{cases} \quad (3)$$

where C_{ADD} is the damping coefficient of the SAS system, $\dot{Z}_s$ is the absolute velocity of sprung mass, $\ddot{Z}_s$ is the absolute acceleration of sprung mass, and $\dot{Z}_u$ is the absolute velocity of unsprung mass.

Case 2 (GH approach). The GH approach can be viewed as an opposite side of the ADD approach and it mainly concerns the control of the tire deformation. By reducing the tire deformation, the dynamic tire load can be decreased. The GH approach considers the state of the unsprung mass in its control process, and the schematic diagram of the GH approach in the SAS system is illustrated in Figure 3.

The damping force of the SAS system with GH approach can be described as

$$F_{\text{GH}} = \begin{cases} C_{\text{GH}}\dot{Z}_u, & \text{when } \dot{Z}_u\left(\dot{Z}_s - \dot{Z}_u\right) \leq 0 \\ 0, & \text{when } \dot{Z}_u\left(\dot{Z}_s - \dot{Z}_u\right) > 0, \end{cases} \quad (4)$$

where C_{GH} is the damping coefficient of the SAS system.

Case 3 (traditional hybrid-SH and GH-strategy). The traditional hybrid-SH and GH-strategy introduced in this work is a straightforward hybrid tuning method between the SH and the GH approach, as shown in Figure 5. The damping force of the SAS system with this method can be represented as
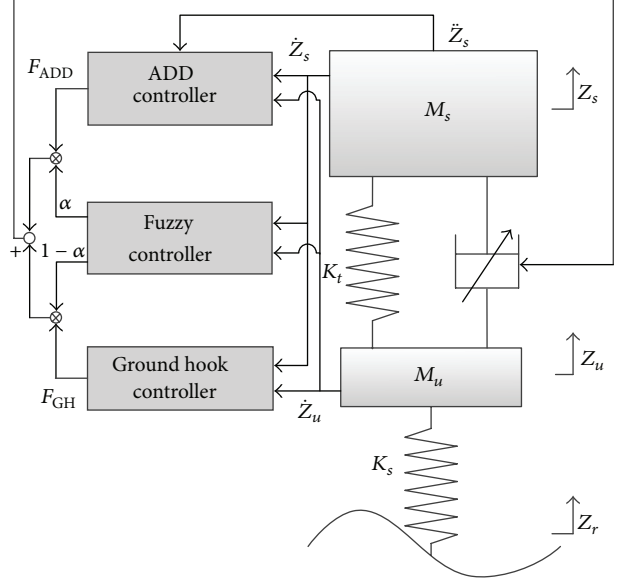
$$F_{\text{HSG}} = \beta F_{\text{SH}} + \left(1 - \beta\right) F_{\text{GH}}, \quad (5)$$

where β is the weighting coefficient used for determining the contribution of the SH approach and the GH approach to the final damping force. With different settings of the β values, various suspension performances can be achieved. To simplify the calculation, β is defined as $\beta \in [0, 1]$. Furthermore, in light of the balance between the SMA and DTL, β is set as 0.5. F_{GH} is the damping force with the GH approach (regarding its control rules, refer to Case 2). Note that F_{SH} here is the damping force with the sky hook approach and it complies with the following rules:

$$F_{\text{SH}} = \begin{cases} C_{\text{SH}}\dot{Z}_s, & \text{when } \dot{Z}_s\left(\dot{Z}_s - \dot{Z}_u\right) \geq 0 \\ 0, & \text{when } \dot{Z}_s\left(\dot{Z}_s - \dot{Z}_u\right) < 0, \end{cases} \quad (6)$$

where C_{SH} is the damping coefficient of the SAS system.

Case 4 (proposed fuzzy-hybrid-ADD and GH-strategy). Obviously, the simple tuning method (i.e., the straightforward tuning method for hybrid strategy used in Case 3) between the two approaches cannot meet the variable state of the vehicle dynamics. So, a more suitable tuning method, which can not only combine the two individual control methods but also coordinate between the methods, is more desirable.

The fuzzy logic method is used to communicate and coordinate between the ADD and GH approaches for the proposed control strategy. The schematic diagram of the proposed system with fuzzy controlled hybrid-ADD and GH-strategy is shown in Figure 6. As shown in Figure 6, with the dynamic response of the SAS system, the absolute velocity of the sprung mass and absolute velocity of the unsprung mass are first delivered to the sole ADD controller, the sole GH controller, and the fuzzy controller, respectively. With the received signals, the ADD controller and GH controller
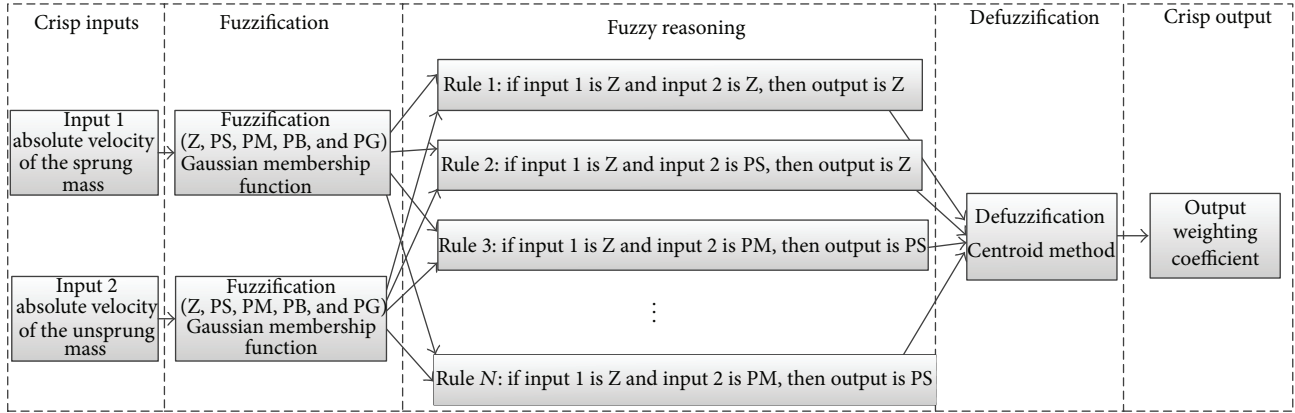
FIGURE 7: Flowchart of the fuzzy controller.

TABLE 2: Rules of the fuzzy controller.

β				$\dot{Z}_s$		
		Z	PS	PM	PS	PG
	Z	Z	Z	PS	PS	PM
	PS	Z	PS	PM	PM	PB
$\dot{Z}_u$	PM	PS	PM	PM	PB	PB
	PB	PS	PM	PB	PB	PG
	PG	PM	PB	PB	PG	PG

compute the corresponding damping force with their own rules. As for the fuzzy controller, the received signal is used to calculate the weighting coefficient relative to the tuning of the hybrid-ADD and GH-strategy. After that, the calculated weighting coefficients are then separately distributed to the ADD controller and the GH controller for further processing. By multiplying respective weighting coefficient, the damping force from each of the two approaches (i.e., ADD approach and GH approach) can be computed, and then the final damping force of the proposed system can be obtained.

In the fuzzy controller, there are five parts, including crisp inputs, fuzzification, fuzzy reasoning, defuzzification, and crisp output, as shown in Figure 7. First of all, the absolute velocity of the sprung mass and the absolute velocity of the unsprung mass are regarded as the inputs with crisp numbers. The domains of discourse of them are $[-0.04, 0.04]$ and $[-0.025, 0.025]$, respectively. Next, the Gaussian function is adopted as the membership function to fuzzify the measured crisp inputs into soft fuzzy variables, and five linguistic variables, Zero "Z," Positive Small "PS," Positive Medium "PM," Positive Big "PB," and Positive Great "PG," are defined. Then, Mamdani logic is utilized as the method of fuzzy reasoning according to the rule base described in Figure 8 and Table 2. After that, defuzzification is carried out by using centroid method to convert the fuzzy value represented by membership function into crisp output. Finally, as the crisp output, the weighting coefficient with the domain of discourse $[0, 1]$ is exported.
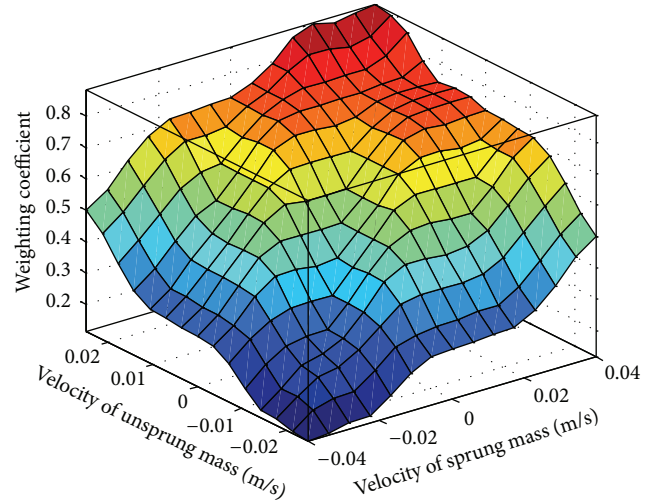

FIGURE 8: Compositional rule of inference for the fuzzy controller.

4. Numerical Results and Analysis

To examine the performance of the proposed strategy, numerical simulations are conducted based on the models constructed in Section 2. The numerical results with various control strategies are shown in Figures 9 and 10. In addition, to clearly figure out the improvement of proposed strategy, the RMS values of the SMA and DTL are also computed for each of the control strategies, as described in Table 3.

Figure 9 shows the SMA with different control strategies. It can be seen that ADD approach achieves the best performance as compared with other cases while GH approach performs worst. However, in Figure 10, the GH approach excels the other strategies while ADD performs worst in the DTL. The reasons for the above results lie in the fact that the ADD approach and GH approach are particularly designed for improving the SMA and DTL, respectively. Moreover, in Figures 9 and 10, the proposed strategy outperforms the traditional hybrid-SH and GH-strategy in terms of the SMA and DTL, which means the fuzzy controller takes effect in the coordination of the two individual approaches.

TABLE 3: Control performance with various control strategies.

Item	Methods			
	ADD	GH	Hybrid-SH and GH	Fuzzy tuning hybrid-ADD and GH
RMS of the SMA	**1.099**	2.033	1.710	1.226
RMS of the DTL	8347	**4300**	6979	5495
Overall performance	0.471	0.423	0.590	**0.196**
Improvement*	58.39%	53.66%	66.78%	/

Note: * means the overall performance improvement of the proposed strategy compared to the method of current item.
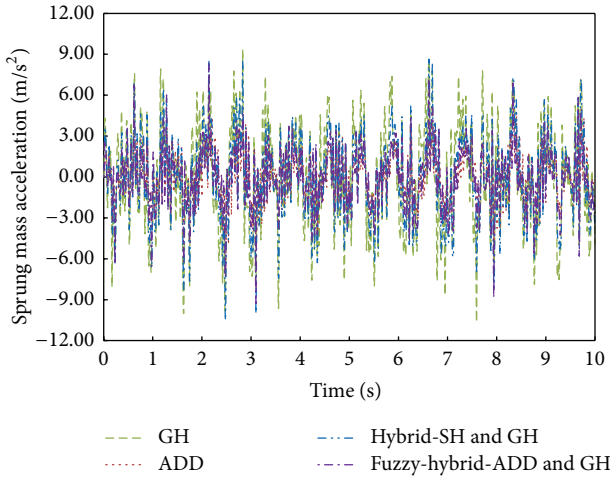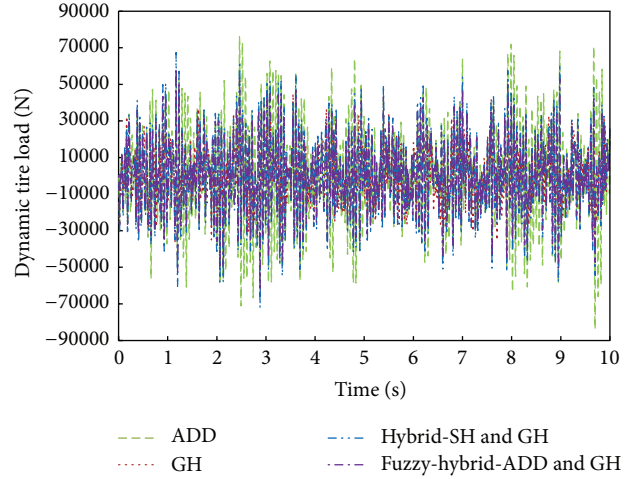

FIGURE 9: Comparison of sprung mass acceleration.

FIGURE 10: Comparison of dynamic tire load.

In addition to the comparison with numerical results, a fitness function is designed to further evaluate the improvement of the proposed strategy as compared to other strategies. The fitness function is presented as

$$\eta_o = w_{SMA} \left(\frac{RMS_{SMA} - RMS_{SMA\text{-}min}}{RMS_{SMA\text{-}min}} \right) + w_{DTL} \left(\frac{RMS_{DTL} - RMS_{DTL\text{-}min}}{RMS_{DTL\text{-}min}} \right), \tag{7}$$

where η_o is the overall performance of the control strategy and w_{SMA} and w_{DTL} are the normalization coefficient which can transform the objective RMS value to the certain range $[0, 1]$ so as to ensure that each objective RMS value has the same contribution to the fitness function. In this work, w_{SMA} and w_{DTL} are equal to each other and set as 0.5. Then, with the fitness function, the overall performance of each control strategy can be quantified to the same level.

With the above method, the overall performance for each of the control strategies can be calculated. It can be seen from Table 3 that, compared with the ADD strategy, the GH-strategy, and the traditional hybrid-SH and GH-strategy, the overall performance of the proposed strategy is improved by 58.39%, 53.66%, and 66.78%, respectively.

5. Conclusion

Aiming to improve the ride quality and road friendliness, a fuzzy controlled hybrid-ADD and GH-strategy has been developed for a semiactive suspension system of heavy-duty vehicles. In the design of the proposed control strategy, the fuzzy controller has been successfully employed as the tuning method of the hybrid strategy and was proved to be effective in the coordination of the ADD approach and GH approach. To examine the performance of the proposed strategy, a quarter-vehicle model, as well as some comparative cases, including sole ADD approach, sole GH approach, and traditional hybrid-SH and GH-strategy, was introduced. Numerical results show that the sole ADD approach and sole GH approach perform best in the SMA and DTL, respectively, while the proposed strategy holds a good performance in the overall performance of the heavy-duty vehicle. In general, this paper provides a new solution for the design of road friendly SAS system of heavy-duty vehicles.
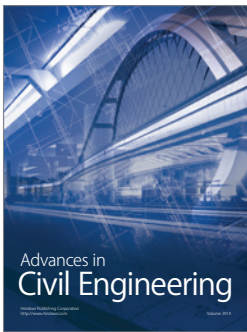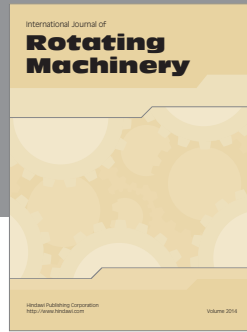
Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

References

[1] M. Valášek, W. Kortüm, Z. Šika, L. Magdolen, and O. Vaculín, "Development of semi-active road-friendly truck suspensions," *Control Engineering Practice*, vol. 6, no. 6, pp. 735–744, 1998.

[2] D. Karnopp, M. J. Crosby, and R. A. Harwood, "Vibration control using semi-active force generators," *Journal of Engineering for Industry*, vol. 96, no. 2, pp. 619–626, 1974.

[3] D. Sammier, O. Sename, and L. Dugard, "Skyhook and H-infinity control of semi-active suspensions: some practical aspects," *Vehicle System Dynamics*, vol. 39, no. 4, pp. 279–308, 2003.

[4] J. L. Yao, S. Taheri, S. M. Tian, Z. N. Zhang, and L. Shen, "A novel semi-active suspension design based on decoupling skyhook control," *Journal of Vibroengineering*, vol. 16, no. 3, pp. 1318–1325, 2014.

[5] R. Caponetto, O. Diamante, G. Fargione, A. Risitano, and D. Tringali, "A soft computing approach to fuzzy sky-hook control of semiactive suspension," *IEEE Transactions on Control Systems Technology*, vol. 11, no. 6, pp. 786–798, 2003.

[6] S. M. Savaresi, E. Silani, and S. Bittanti, "Acceleration-Driven-Damper (ADD): an optimal control algorithm for comfort-oriented semiactive suspensions," *Journal of Dynamic Systems, Measurement and Control—Transactions of the ASME*, vol. 127, no. 2, pp. 218–229, 2005.

[7] L. Balamurugan and J. Jancirani, "An investigation on semi-active suspension damper and control strategies for vehicle ride comfort and road holding," *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, vol. 226, no. 8, pp. 1119–1129, 2012.

[8] M. Valasek and W. Kortum, "Road-friendly trucks," *Structural Dynamics*, vol. 1-2, pp. 855–860, 1999.

[9] J.-H. Koo, M. Ahmadian, M. Setareh, and T. M. Murray, "In search of suitable control methods for semi-active tuned vibration absorbers," *Journal of Vibration and Control*, vol. 10, no. 2, pp. 163–174, 2004.

[10] A. Zin, O. Sename, P. Gaspar, L. Dugard, and J. Bokor, "Robust LPV-H infinity control for active suspensions with performance adaptation in view of global chassis control," *Vehicle System Dynamics*, vol. 46, no. 10, pp. 889–912, 2008.

[11] L. Flores, A. Drivet, R. A. Ramírez-Mendoza, O. Sename, C. Poussot Vassal, and L. Dugard, "Hybrid optimal control for semi-active suspension systems," in *Proceedings of th 10th Mini Conference on Vehicle System Dynamics, Identification and Anomalies (VSDIA '06)*, pp. 505–512, Budapest University of Technology and Economics, Budapest, Hungary, November 2006.

[12] Z. Xie, P. K. Wong, J. Zhao, T. Xu, K. I. Wong, and H. C. Wong, "A noise-insensitive semi-active air suspension for heavy-duty vehicles with an integrated fuzzy-wheelbase preview control," *Mathematical Problems in Engineering*, vol. 2013, Article ID 121953, 12 pages, 2013.

[13] S.-B. Choi, D.-W. Park, and M.-S. Suh, "Fuzzy sky-ground hook control of a tracked vehicle featuring semi-active electrorheological suspension units," *Journal of Dynamic Systems, Measurement and Control*, vol. 124, no. 1, pp. 150–157, 2002.

[14] S. H. Ha, S. B. Choi, G. S. Lee, and W. H. Yoo, "Control performance evaluation of railway vehicle MR suspension using fuzzy sky-ground hook control algorithm," *Journal of Physics: Conference Series*, vol. 412, Article ID 012042, pp. 1–5, 2013.

[15] Z. C. Xie, P. K. Wong, J. Zhao, and T. Xu, "Design of a denoising hybrid fuzzy-pid controller for active suspension systems of heavy vehicles based on model adaptive wheelbase preview strategy," *Journal of Vibroengineering*, vol. 17, pp. 883–904, 2015.

Journal of
Engineering

The Scientific
World Journal

International Journal of
Rotating
Machinery

Journal of
Sensors

International Journal of
Distributed
Sensor Networks

Advances in
Civil Engineering

Journal of
Control Science
and Engineering

Journal of
Robotics

Hindawi

Submit your manuscripts at
http://www.hindawi.com

Journal of
Electrical and Computer
Engineering

Advances in
OptoElectronics

VLSI Design

International Journal of
Navigation and
Observation

Modelling &
Simulation
in Engineering

International Journal of
Aerospace
Engineering

International Journal of
Chemical Engineering

International Journal of
Antennas and
Propagation

Active and Passive
Electronic Components

Shock and Vibration

Advances in
Acoustics and Vibration