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# Adaptive tracking control for active suspension systems with non-ideal actuators

Huihui Pan [a,b], Weichao Sun [a,*], Xingjian Jing [b,c], Huijun Gao [a], Jianyong Yao [d]

[a] *Research Institute of Intelligent Control and System, Harbin Institute of Technology, Harbin 150001, China*
[b] *Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, China*
[c] *Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China*
[d] *School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China*

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ABSTRACT

As a critical component of transportation vehicles, active suspension systems are instrumental in the improvement of ride comfort and maneuverability. However, practical active suspensions commonly suffer from parameter uncertainties (e.g., the variations of payload mass and suspension component parameters), external disturbances and especially the unknown non-ideal actuators (i.e., dead-zone and hysteresis nonlinearities), which always significantly deteriorate the control performance in practice. To overcome these issues, this paper synthesizes an adaptive tracking control strategy for vehicle suspension systems to achieve suspension performance improvements. The proposed control algorithm is formulated by developing a unified framework of non-ideal actuators rather than a separate way, which is a simple yet effective approach to remove the unexpected nonlinear effects. From the perspective of practical implementation, the advantages of the presented controller for active suspensions include that the assumptions on the measurable actuator outputs, the prior knowledge of nonlinear actuator parameters and the uncertain parameters within a known compact set are not required. Furthermore, the stability of the closed-loop suspension system is theoretically guaranteed by rigorous mathematical analysis. Finally, the effectiveness of the presented adaptive control scheme is confirmed using comparative numerical simulation validations.


## 1. Introduction

In recent years, suspension systems have been a highlighted research topic due to their important role in transportation vehicles [1–5]. The popularity of suspensions lies in their practical performance requirements, such as ride comfort and road holding. Generally speaking, suspension systems can be classified into three categories: passive, semiactive, and active suspensions [6,7]. Passive suspensions mainly consist of traditional springs and dampers mounted between the vehicle body (sprung mass) and wheel-axle assembly (unsprung mass). Passive ones are inadequate in simultaneously achieving the performance improvements of ride comfort and road holding, because these two criteria require different spring and damper properties and conflict with each other. Semiactive suspensions utilize variable dampers or other variable dissipation components to provide considerable improvements over passive systems, but they are still limited in improving ride comfort performance [8–10]. Active suspensions provide controlled actuators placed between the vehicle body and wheel-axle in parallel with the suspension elements,

* Corresponding author.
*E-mail address:* w.sun@hit.edu.cn (W. Sun).

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**Nomenclature**

| | |
|---|---|
| $m_s$, $m_u$ | the masses of the sprung (car chassis) and the unsprung (wheel assembly) |
| $z_s$, $z_u$, $z_r$ | the displacements of the sprung mass, the unsprung mass and the road input |
| $\dot{z}_s$, $\dot{z}_u$, $\dot{z}_r$ | the velocities of the sprung mass, the unsprung mass and the road input |
| $F_d$, $F_s$ | the forces produced by the spring and damper |
| $F_t$, $F_b$ | the elasticity force and damping force of the tires |
| $k_s$, $k_{s_n}$ | the stiffness coefficients of linear and nonlinear terms |
| $b_{c_1}$, $b_{c_2}$ | the damping coefficients linear and nonlinear terms |
| $k_f$, $b_f$ | the stiffness and damping coefficients of the tire |
| $f_l(t)$ | the bounded external disturbance and unmodelled dynamics |
| $\nu(t)$ | the control input signal |
| $N(\nu(t))$ | the non-ideal actuator control output signal |
| $x_i$, $z_i$ | system states and coordinate transformations |
| $\hat{\bullet}$, $\tilde{\bullet}$ | estimate of $\bullet$ and adaption error of $\bullet$ |
| $k_i$, $\gamma_i$, $\Gamma$ | positive design parameters |

which have the ability to create the desired force for both adding and dissipating energy from the system, to achieve certain performance objectives [11–14]. Compared with passive and semiactive suspension systems, active suspensions possess more effective in the realization of significant performance improvements [15]. Thus, numerous attention has been paid to the researches of active suspension systems in both industry and academia.

It is noted that active suspension systems are difficult to establish their precise mathematical models since the parameter uncertainties and external disturbances always exist in practical scenarios [16]. The parameter uncertainties, or more specifically, refer to the uncertain sprung mass, which changes with the loading conditions, such as the unknown masses of passengers and payload; and the uncertain suspension component parameters that vary with the application environment, such as fatigue, wear and aging. These uncertainties/disturbances might result in degraded suspension performance and even lead to the instability of control systems if they are not considered in the control law design process. At present, for active suspension systems with uncertain parameter effects, the related studies are still at the elementary stage, and there are much less reported works than those for time-invariant suspensions. In the existing literatures, some studies are concentrated on the intelligence learning algorithms, such as fuzzy logic [17,5], established upon approximate suspension models, and on this topic, many interesting results are obtained, e.g., [18,19]. Nonetheless, these intelligent approaches produce numerous learning parameters or gains, which may need to implement considerable effort in determining suitable parameters if the controlled plant has uncertain parameters. Besides those learning-based control methods, adaptive technique is a good alternative approach to resolve the uncertainty issues [20]. In [21], a robust adaptive-based control method is proposed to achieve the optimized suspension objective with a predefined-time trajectory planning approach. The authors in [18] used the adaptive sliding-mode with T-S fuzzy approach to handle the uncertainty caused by the variation of the sprung mass. However, the unknown parameters of the suspension components are ignored in the above two methods.

In addition, similar to other mechatronic systems [22–29], the actuator is the primary part of the design for realizing the desired control objectives of vehicle suspensions. However, non-ideal actuator properties, such as dead-zone [30–32] and hysteresis [33] nonlinearities, extensively exist in practical actuators and mechanical connections [34]. If these non-ideal nonlinearity factors are ignored, the performance of the control approaches may suffer severe degradation in the presence of actuator nonlinearities [16,35,36]. Different studies have attempted to adapt the inverse compensation methods for non-ideal actuators [37–39]. The common feature of these inverse schemes is that they mainly based on the construction of an inverse dynamic to mitigate the effect of the actuator nonlinearities, see details in [37–39]. When the parameters of the non-ideal actuator nonlinearities are known, a perfect inversion of the input nonlinearity can be constructed directly for compensating its effect completely. Nevertheless, in fact, the actuator output of the suspension is often difficult to measure and the actuator nonlinearity parameters are hardly known completely.

As a brief summary, motivated by the aforementioned observation for suspension systems, the following important problems remain unresolved or require further improvements: (1) Existing suspension controllers are arduous to determine the proper value of control parameters, particularly when active suspensions have dynamic properties with parameter uncertainties inevitably. From a viewpoint of real-time implementation, these difficulties limit their further application. Moreover, the suspension may suffer from the effect of external disturbance (e.g., unknown frictions). This uncertain factor will affect the control performance. (2) Most existing adaptive controllers for suspension systems require the uncertain parameters within a known compact set (e.g., the upper and lower bounds of the sprung mass), and involve exact suspension component information (e.g., stiffness and damping coefficients), even neglect the conditions of uncertainties. As introduced earlier, the accurate values of suspension systems are generally difficult or impractical to be identified. (3) Almost all existing control schemes for control law design with non-ideal actuator nonlinearities need the actuator output to be measured or the exact values of actuator parameters, and only can be adapted for one class of actuator nonlinearity, which are insufficient in handling the effects of unknown non-ideal input nonlinearities. Therefore, without the direct measurement of actuator output, how to effectively compensate the effects of non-ideal actuator nonlinearities with parameter uncertainties has always been a practically important issue, and the investigation on controller design and stability analysis of uncertain suspension systems have also been an urgent demand.