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# Adaptive prescribed performance control of half-car active suspension system with unknown dead-zone input

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ABSTRACT

This paper proposes a novel adaptive control scheme for half-car active suspension system (HCASS) with unknown dead-zone input. Under the proposed control framework, the overall HCASS is divided into two subsystems. The proposed controller is designed based on the first subsystem, and the second subsystem is regarded as zero dynamics of HCASS. For the first subsystem, a new robust adaptive strategy is first constructed to compensate the adverse effects of unknown dead-zone input nonlinearities. Further, in order to ensure some important state variables within the given restrictive conditions all the time, a novel prescribed performance control strategy (PPC, for short) is designed. For the second subsystem, the corresponding stability analysis of zero dynamics is presented. Finally, the solution of the resulting closed-loop system is ensured to be uniformly ultimately bounded, and the effectiveness of the proposed approach is illustrated by a strict and complete simulation analysis.

## 1. Introduction

Advanced suspension systems are mechatronic systems that play a significant role in vehicles [1]. These suspension systems ensure that vehicles can provide a better drive experiences such as maneuverability, riding comfort, and safety for drivers [2]. During the past few decades, the research interests focus on three different kinds of suspension systems: (i) passive suspension systems, (ii) semi-active suspension systems, and (iii) active suspension systems.

The passive suspension system is usually made up of dampers and springs. This kind system doesn't perform well in improving ride comfort and road handling capacity simultaneously owning to the passivity of these components. The passivity means the coefficients of springs and dampers are fixed in the presence of various kinds of road disturbances. In view of the disadvantages of passive suspension systems, variable dampers are added to the semi-active suspension systems to ensure these systems can achieve significant improvements over the passive suspension systems by constantly adjusting the rate of energy dissipation [3–8]. Even though the performance improvements have been made, it still cannot satisfy the drivers and passengers' needs for the suspension systems. Therefore, active suspension system attracts more and more researchers' attention for it has the ability to change energy storage by using an actuator parallel to suspension elements (e.g., dampers and springs). The actuator component is installed between the car body and the wheel-axe, and is able to add or dismiss forces from the system ([9–24] and references therein). The parameter uncertainty of such system is

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considered in the work [19]. In [23], L2 gain state derivative feedback controller is proposed to solve the parametric uncertainty problem of uncertain quarter vehicle suspension systems. In [18], the author proposes a saturated adaptive robust control for active suspension system with saturated control input. An adaptive fault tolerant control scheme is designed to deal with the random actuator fault in [20]. Recently, an interesting integrated seat and suspension model that includes a quarter-car suspension, a seat suspension, and a 4-degree-of-freedom (DOF) driver body model is first presented in [24], and based on the integrated model, an state feedback controller is designed to minimize the driver head acceleration under road disturbances. In [25], energy saving problem is studied, a constrained $H_\infty$ controller is designed to apply the self-powered suspension criterion and energy regeneration implementation scheme. In [26,27], the fuzzy theory based sliding mode controllers are proposed to solve the vibration problem for uncertain suspension systems.

As we know, dead-zone input nonlinearity is a common but should never be underestimated problem [28–32]. In early works [28,29], a control scheme is designed based on adaptive technique. In work [30], the author proposes an adaptive neural network controller where the neural network approximation method is applied to deal with the dead-zone property. With the use of the backstepping method, the adaptive output feedback controller is designed in the work [29,31] for a class of nonlinear systems with dead-zone input nonlinearity. Through modelling the dead-zone input as a combination of linear term and disturbance-like term, Wang et al. [32] proposes an adaptive feedback controller for the symmetric dead-zone input problem. Ibrir et al. [33] further relaxes the assumption and designs the state feedback controller to deal with non-symmetric dead-zone input problem.

Prescribed performance control (PPC), which belongs to constraint control, ensures the convergence rate no less than a prescribed value, exhibiting a maximum overshoot less than a sufficiently small constant. The output or tracking error can approach to an arbitrarily small residual set. Contributions in PPC may be found in [34–38].

Considering there are few works dealing with the unknown dead-zone input problem in HCASS, we creatively propose a brand-new adaptive control scheme to solve such problem in this work. Further, a novel PPC strategy is designed to ensure some state variables within the given restrictive conditions all the time. The work is organized as follows: Section 2 presents HCASS model and unknown dead-zone input model in detail. Then, the controller and adaptive law are given in Section 3. In Section 4 the detailed stability proofs of the zero dynamics are presented. In Section 5, the corresponding simulation results are presented to illustrate the effectiveness of the proposed control scheme. Finally, the conclusion is given in Section 6.

*Notations:* Throughout this paper, $(\cdot)^T$ stands for the transpose, $\lambda_{max}(\cdot)$ and $\lambda_{min}(\cdot)$ denote the maximal and the minimal eigenvalues, respectively. $\Gamma(u(t))$ represents the system control input with dead-zone property.

## 2. Problem formulation

In this work, a HCASS is taken into consideration, as shown in Fig. 1. The overall HCASS model is presented as follows:

$$\begin{aligned}
m_s\ddot{z}_c(t) &= -k_{sf}(z_{sf}-z_{uf}) - c_{sf}(\dot{z}_{sf}-\dot{z}_{uf}) + \Gamma_2(u_r) - k_{sr}(z_{sr}-z_{ur}) - c_{sr}(\dot{z}_{sr}-\dot{z}_{ur}) + \Gamma_1(u_f) \\
I\ddot{\varphi} &= -ak_{sf}(z_{sf}-z_{uf}) - ac_{sf}(\dot{z}_{sf}-\dot{z}_{uf}) - b\Gamma_2(u_r) + bk_{sr}(z_{sr}-z_{ur}) + bc_{sr}(\dot{z}_{sr}-\dot{z}_{ur}) + a\Gamma_1(u_f) \\
m_{uf}\ddot{z}_{uf} &= k_{sf}(z_{sf}-z_{uf}) + c_{sf}(\dot{z}_{sf}-\dot{z}_{uf}) - k_{tf}(z_{uf}-z_{rf}) - c_{tf}(\dot{z}_{uf}-\dot{z}_{rf}) - \Gamma_1(u_f) \\
m_{ur}\ddot{z}_{ur} &= k_{sr}(z_{sr}-z_{ur}) + c_{sr}(\dot{z}_{sr}-\dot{z}_{ur}) - k_{tr}(z_{ur}-z_{rr}) - c_{tr}(\dot{z}_{ur}-\dot{z}_{rr}) - \Gamma_2(u_r)
\end{aligned} \tag{1}$$

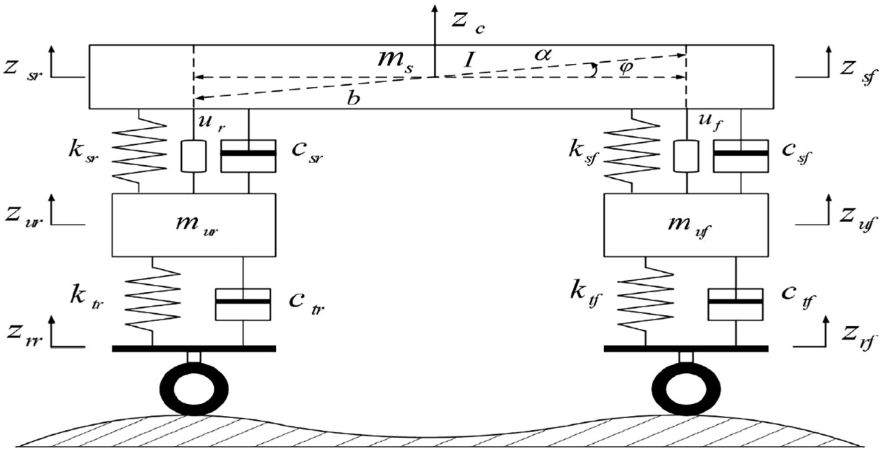

**Fig. 1.** The structure of the half-car active suspension system.