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Disturbance observer based sliding mode control of active suspension systems

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ABSTRACT

In this paper, a novel scheme to reduce the acceleration of the sprung mass, used in combination with sliding mode control, is proposed. The proposed scheme estimates the effects of the uncertain, nonlinear spring and damper, load variation and the unknown road disturbance. The controller needs the states of sprung mass only, obviating the need to measure the states of the unsprung mass. The ultimate boundedness of the overall suspension system is proved. The efficacy of the method is verified through simulations for three different types of road profiles and load variation and the scheme is validated on an experimental setup. The results are compared with passive suspension system.

1. Introduction

There is a great interest in active suspension systems because of the improvement in ride comfort made possible by such systems. The suspension system of a vehicle is an uncertain nonlinear system subjected to an unknown road disturbance. The design of an active suspension system is a challenge because the ride comfort is to be improved in the presence of uncertainties and unknown road disturbance while maintaining good road holding and operating within the rattle space limitations [1,2].

During the last three decades, many diverse control strategies, such as optimal control [3], adaptive control [4–7], model reference adaptive control [8–10], H_∞ [11], LQG control [12] among many others, have been employed in active suspension systems. Adaptive backstepping control for active suspension systems with hard constraints is proposed in [13] for stabilizing the attitude of the vehicle while improving the ride comfort. In [14] a backstepping control is proposed to compensate for actuator lag while in [15] an adaptive robust control is proposed to cope up with actuator saturation.

In general, it is difficult to find an accurate model of the suspension system. For this reason, many researchers have proposed solutions based on model free strategies like the fuzzy control [16], fuzzy control with genetic algorithms and neural network [17,18]. Another well known strategy for control of uncertain systems affected by unmeasurable disturbances is the sliding mode control (SMC) strategy. The sliding mode control is not model free but can guarantee invariance for matched uncertainties and disturbances having a known bound. The application of SMC and its combinations with other strategies are reported in [9,10,19–21].

The performance of an active suspension system can be improved if accurate information about road profile is obtained in real time. In the literature, efforts to obtain this information directly and indirectly are reported. Some researchers have tried to obtain this information directly using special sensors or by using lead vehicles as sensors. A system with preview control employing a vehicle mounted preview sensor is proposed in [22,23] while the use of the lead vehicle in a convoy as preview sensor is proposed in [24].

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Some researchers have obtained the information about the uncertainties and the road disturbance indirectly, obviating the need for employing special sensors. In [25,26], a function approximation technique is used to approximate the unknown function containing uncertainty and the road disturbance with an adaptive sliding mode control. In [27] an inertial delay control that estimates the road disturbance is proposed for a sky-hook active suspension system. A drawback of this scheme is that it requires the states of the unsprung mass.

The main motivation of this paper is to improve the ride comfort which largely depends on the acceleration of the sprung mass. The acceleration of the sprung mass results from an unknown road profile and therefore a control scheme that can estimate the effects of the road profile is required. Further, the need to position sensors to measure the states of the unsprung mass is to be obviated and the drawback of conventional SMC that needs the knowledge of the bounds of uncertainty is to be overcome. In this paper, an active suspension system that uses the sliding mode control along with a Disturbance Observer (DO) is proposed. In the conventional sliding mode control, the uncertainties and disturbances can be compensated if their bounds are known. The road disturbance can vary considerably even in a small journey, making it difficult to obtain the bounds of the uncertainty that are not too conservative. In order to remove this difficulty, a scheme that estimates the effect of uncertainty and the road disturbance is proposed in this paper. The scheme for estimation is a modified version of the disturbance observer proposed in [28]. A preliminary version of this paper appeared in [29]. Salient features of this paper are as follows:

- The proposed scheme estimates the effect of the road disturbance, nonlinearities and uncertainties of the suspension system and then negates them using control.
- The scheme does not require the states of the unsprung mass thereby reducing the sensor requirement.
- Unlike the conventional sliding mode control, no knowledge of bounds on uncertainties and disturbances is required.
- A single controller works satisfactorily under various loading conditions and road profiles.
- Stability of the overall system is proved.

The paper is organized as follows: a quarter car model and the dynamic equations are explained in Section 2 while Section 3 explains the sliding mode control. The disturbance observer is explained in Section 4. In Section 5 the stability of the overall system is proved and the ultimate bounds on estimation error and the sliding variable are calculated. The efficacy of the proposed controller is illustrated by simulation results in Section 6 and the scheme is validated on an experimental setup in Section 7. The conclusion is given in Section 8.

2. Problem statement

Consider the quarter car model of suspension system shown in Fig. 1. The sprung mass $m_s(t)$ is the mass of the car body, passengers, frame, internal components and it may vary according to the passenger loading condition of the car. It is supported by the suspension system consisting of a spring k_s and a damper c_s. The spring is modelled by a linear stiffness coefficient k_{1s} and nonlinear stiffness coefficient k_{2s} and the damper is modelled by linear damping coefficient c_1 and nonlinear damping coefficient c_2. The mass of the wheel, tyre, brake and suspension linkage mass is referred to as unsprung mass m_u which is supported by the tyre modelled as a combination of linear spring and linear damper with coefficients k_t and c_t respectively. In an active suspension system, in addition to these passive components, an actuator is connected between the sprung mass and the unsprung mass. The actuator generates a control force u so as to improve the ride comfort.

It is assumed that no a priori information is available about the unknown road profile. The vertical road disturbance acting on the unsprung mass is denoted by z. The vertical displacements of the sprung mass and unsprung mass with respect to their static positions are denoted by x_s and x_u respectively. Next, the dynamic equations of the suspension system are expressed in the state variable form.

Let the state $x = [x_1\ x_2\ x_3\ x_4]^T$ be defined as

$$x_1 = x_s, \quad x_2 = \dot{x}_s, \quad x_3 = x_u, \quad x_4 = \dot{x}_u \tag{1}$$

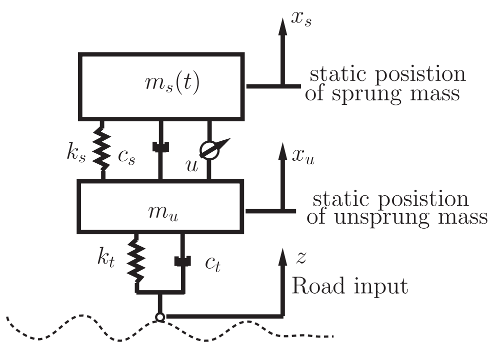

Fig. 1. Quarter car suspension model.