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Velocity-dependent multi-objective control of vehicle suspension with preview measurements

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ABSTRACT

This paper presents a velocity-dependent multi-objective control method to solve the problem of preview control with velocity uncertainty. A half-car model is considered, the Padé approach is used to approximate the preview delay so as to rewrite it in a finite-dimensional description. It is assumed that the forward velocity of the vehicle resides in an interval and can be measured in real time. The controller, whose gain matrix depends on the information of the velocity, is designed by utilizing the polynomial parameter-dependent idea. The design procedure is developed based on homogeneous polynomial parameter-dependent matrices with arbitrary degree, with quadratic and linear parameter-dependent frameworks as special cases of this method. As the degree increases, the proposed controller can yield less conservative result. A linear parameter-dependent (LPV) controller has also been proposed for the system under time-varying velocity. Simulation results illustrate the usefulness and the advantages of the proposed methods.
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1. Introduction

Vehicle suspension is designed to provide isolation of the car body from road disturbances, to support the vehicle static weight, to keep tyres firmly contact with the ground, and to maintain the car body and wheels in appropriate positions. Generally speaking, these requirements are conflicting. For example, ride comfort calls for soft stiffness suspension while road holding needs the opposite. Passive vehicle suspension has limited capacity to deal with these demands, but active vehicle suspension has a great potential to meet the tight performance requirements. This research area has drawn much attention in recent years. Various approaches, such as fuzzy control [1,2], H_∞ control [3–6], adaptive control [7,8], switched control [9], robust control [10,11] and networked control [12], have been proposed to design a suitable control law of active and semi-active suspension.

Preview control is a strategy to utilize the road information to enhance the vehicle suspension performance, it is firstly proposed by Bender [13]. Many researchers have devoted to the improvement of this method, see [14–17]. In general, preview control can be divided into two strategies according to the different methods to obtain the preview information, namely, look-ahead preview and wheelbase preview. The former one obtains the preview information by a sensor, and the latter one obtains information from the system responses under the disturbance at the front wheel. LQ-based optimization approach has been broadly used in suspension design with preview control. This approach is a single objective design method, it calls for a trade-off between different performance requirements. In contrast with single objective method, multi-objective control, which achieves better performance, has been used in suspension design in recent years, see [18–20]. Multi-objective approach with look-ahead preview control of a quarter-car model is introduced in [21] from the view point of discrete-time system. In their work, both the simulation and experiment results show that it is more effective when compared with the look-ahead preview using Linear-Quadratic Gaussian approach.

In preview control, either look-ahead preview or wheelbase preview, the preview time will change according to different vehicle velocities which will introduce uncertainties into the system. However, LQ-based design approach has limited capacity to address the problem when the system is subject to parameter uncertainty. The resulting control may become unstable, when system parameters change. One can see numerous works related to uncertain systems, for example, see [22–26]. Robust control techniques have been utilized in suspension design to handle the system with uncertainties. Du et al. [27] design a robust velocity-dependent yaw moment controller for a system with uncertain vehicle speed and cornering stiffness. A semi-active H_∞ control with parameter uncertainties on sprung mass and ER damper time constant given in a polytopic form is presented in [28]. Robust quantized control is investigated for active suspension system with

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polytopic parameter uncertainties in [29]. Li et al. [30] design a H_∞ controller for a half-car suspension system with input delay, the vehicle front sprung mass and the rear unsprung mass are modelled as polytopic uncertainty. Sun et al. [31] propose saturated adaptive robust control in response to uncertainties in systems with possible actuator saturation, an antiwindup block has been added in the control strategy, simulation results demonstrate the method can stabilize the vehicle attitude and improve ride comfort. A robust multi-objective controller for a quarter-car model is proposed in [32], but the method may be conservative due to the quadratic framework used. To improve the result in [32], Gao et al. [33] present a load-dependent controller based on affine parameter-dependent Lyapunov function. This method provides less conservative results compared with [33]. By utilizing the parameter-dependent idea, polynomially parameter-dependent Lyapunov function becomes a natural extension of affine parameter-dependence to reduce the conservatism. Chesi et al. [34] investigate the stabilization of the systems with respect to real parametric uncertainty through homogeneous parameter-dependent quadratic Lyapunov functions. Oliveira and Peres [35] propose a systematic procedure to generate a family of linear matrix inequality (LMI) conditions assuring the existence of a homogeneous quadratic Lyapunov function. These researchers also investigate the performance-based control of uncertain systems with homogeneous polynomially parameter-dependent Lyapunov function, see [36,37]. Gao et al. [38,39] design robust H_2 and H_∞ filtering of linear uncertain system with a structured polynomially parameter-dependent approach, the results show that the proposed filters have better performance.

Previous works on preview control have often unrealistically assumed that the velocity of the vehicle is fixed, in this work we formulate a systematic procedure to design a velocity-dependent multi-objective preview control solution for vehicle suspension. Since the cost of laser sensor is high, and look-ahead preview may have unreliable information at times, wheelbase preview strategy is utilized as the preview information obtained method, and half-car model is considered. In order to rewrite in a finite-dimensional description, the preview information is incorporated to a half-car model through Padé approximation of the delay. It is assumed that the forward velocity of the vehicle resides in a prescribed interval and can be measured online. Homogeneous polynomially parameter-dependent approach is used to design the controller, so that quadratic and linear parameter-dependent frameworks are included in this approach as special cases. As the degree increases, less conservative controller is obtained. On the other hand, a linear parameter varying (LPV) controller is proposed for the velocity-varying case. The merits of the proposed methods are demonstrated with simulation results.

The rest of this paper is organized as follows. The problem of velocity-dependent multi-objective controller design for uncertain vehicle suspension system is formulated in Section 2. Section 3 presents the controller synthesis results by utilizing the homogeneous polynomially parameter-dependent approach, an LPV controller is also proposed for the velocity-varying system. Simulation results illustrating the proposed methods is given in Section 4. Conclusions are given in Section 5.

Notation. Throughout the paper, the superscript T and -1 stand for matrix transposition and matrix inverse, respectively. I_n represents $n \times n$ identity matrix and $0_{n\times m}$ represents $n \times m$ zero matrix; $\mathbb{R}^{n\times m}$ stands for the set of $n \times m$ real matrix. $p!$ represents the factorial of p for $p \in \{0, 1, 2, \ldots\}$. $e_m^{(n)}$ stands for a $n \times 1$ vector with zero elements except the m-th element being equal to 1. $|\cdot|$ represents the absolute value, $\|\cdot\|$ stands for the Euclidean norm of a vector and its induced norm of a matrix. L_2 represents the Hilbert space of Lebesque square integrable functions. $P > 0$ denotes real symmetric and positive definite matrix; the notation $*$ represents a term that is induced by symmetry.

2. Problem formulation

2.1. Description of half-car model

A half-car model with four degrees of freedom is given in Fig. 1. This model contains heave and pitch modes of the sprung mass. The tyre is simplified to a spring, tyre damping is ignored here since it always much smaller than the suspension damping. In practice, tyre dynamic characteristics are complicated. For interested readers, there are works about the tyre-road contact model, see [40–44]. For this half-car model, assume that the pitch angle is small, and all the springs and dampers are linear, the equations of motion can be given as

$$
\begin{aligned}
M\ddot{z}_c &= f_f + f_r,\\
J\ddot{\theta} &= af_f - bf_r,\\
m_f\ddot{z}_f &= -k_{f2}(\eta_f - \mu_f) - f_f,\\
m_r\ddot{z}_r &= -k_{r2}(\eta_r - \mu_r) - f_r,
\end{aligned}
\tag{1}
$$

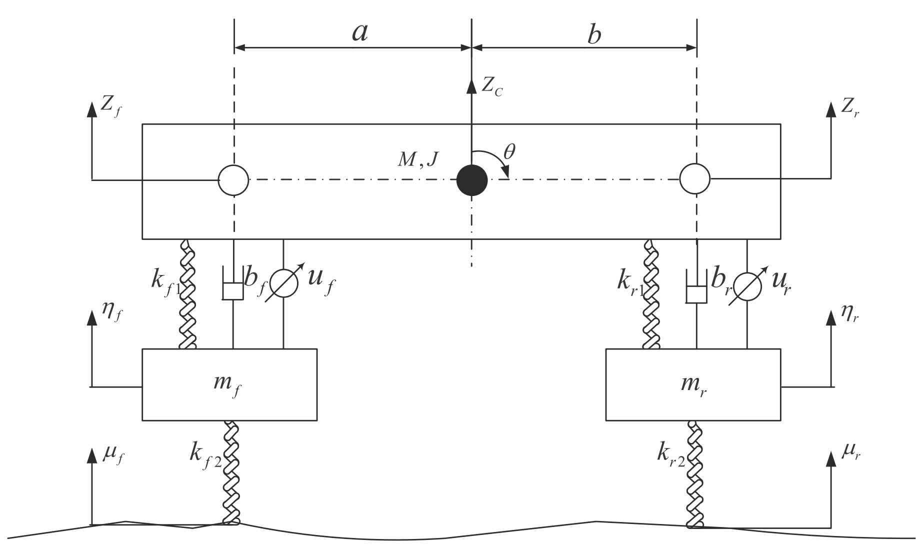

Fig. 1. Half-car model.

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