Mechanical Systems and Signal Processing 94 (2017) 94–110

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Model predictive control of an air suspension system with damping multi-mode switching damper based on hybrid model

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A R T I C L E I N F O

Article history:
Received 13 November 2016
Received in revised form 15 February 2017
Accepted 17 February 2017

Keywords:
Air suspension
Damper
Multi-mode
Hybrid system
Mixed logical dynamical system
Model predictive control

A B S T R A C T

This paper presents the hybrid modeling and the model predictive control of an air suspension system with damping multi-mode switching damper. Unlike traditional damper with continuously adjustable damping, in this study, a new damper with four discrete damping modes is applied to vehicle semi-active air suspension. The new damper can achieve different damping modes by just controlling the on-off statuses of two solenoid valves, which makes its damping adjustment more efficient and more reliable. However, since the damping mode switching induces different modes of operation, the air suspension system with the new damper poses challenging hybrid control problem. To model both the continuous/discrete dynamics and the switching between different damping modes, the framework of mixed logical dynamical (MLD) systems is used to establish the system hybrid model. Based on the resulting hybrid dynamical model, the system control problem is recast as a model predictive control (MPC) problem, which allows us to optimize the switching sequences of the damping modes by taking into account the suspension performance requirements. Numerical simulations results demonstrate the efficacy of the proposed control method finally.

1. Introduction

In recent years, the research field of vehicle suspension has been attracted by semi-active air suspension system [1–3], because it can provide variable stiffness and damping according to different sprung masses and road disturbances. In the past researches of vehicle semi-active air suspension system, different types of dampers with continuously adjustable damping, such as the oil-filled damper with adjustable orifice area [4,5], the magnetorheological (MR) damper [6–8] and the electrorheological (ER) damper [9], are often considered as the actuator for damping adjustment. A variety of control methods, such as the fuzzy interference control [10], the sliding mode control [11] and the multi-model adaptive switching control [12], have also been adopted for the controller design of semi-active air suspension with these dampers. Although these dampers can achieve surpassingly adjustable damping characteristics, lesser amplitude of damping variation doesn't have a significant influence on the control performance of vehicle suspension system actually according to the experimental results [13]. Meanwhile, it is obvious that the realization of continuously adjustable damping is relatively difficult and expensive. Thus, for a vehicle semi-active air suspension system, the damper with multi-stage adjustable damping may be more appropriate and reliable [14].

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http://dx.doi.org/10.1016/j.ymssp.2017.02.033
0888-3270/

Compared with conventional damper with continuously adjustable damping, a new type of damper is presented in this paper to implement the multi-stage adjustable damping characteristics. By just controlling the on-off statuses of two solenoid valves, the hydraulic oil flow paths in the compression and rebound strokes are changed, thus four different damping modes can be achieved. This means, for a vehicle semi-active suspension system with the new damper, effective control strategy should be designed to deliver the requested suspension performance through optimal switching sequences of the four damping modes. However, since the damping mode switches are performed by changing the on-off statuses of solenoid valves, which are typical discrete events, the vehicle semi-active air suspension system with the new damper contains both continuous physical processes and discrete events. Therefore, the existing control approaches only based on continuous dynamic systems may no longer work for the controller design of vehicle semi-active air suspension system with the new damper, which poses challenging hybrid control problem.

Over the past few decades, hybrid systems have attracted the interest of control theorists, because they can reflect the interaction between continuous and discrete dynamics in a unified model [15–17]. Many technological systems, such as thermostat, combined cycle power plants [18] and electro-pneumatic clutch [19], exhibiting both discrete control actions and continuous physical processes, can be accurately described by using hybrid system models. As models are the effective means for system analysis, output prediction and control synthesis, various modeling formalisms for hybrid systems have already been put forward [20–22], and the research of these models are mainly focused on the analysis of hybrid system basic properties, such as stability, reachability and controllability [23]. Among these models, the mixed logical dynamical (MLD) form is capable of modeling a large range of hybrid systems arising in practical applications through linear dynamic equations and inequalities including both continuous and logical variables [24,25]. In particular, the MLD model allows us to recast the system hybrid control problem as a mixed-integer linear/quadratic programming problem, which are suitable to be solved by online numerical solvers [26]. Furthermore, to derive the system MLD model more efficiently, a high-level modeling language, i.e. the hybrid system description language (HYSDEL), has been presented [27], and it will be also applied in this study. The optimal control, which is the crux of achieve our objectives of regulating the switching sequences of the damping modes by considering the suspension performance requirements, is then augmented in the context of a hybrid model predictive control (MPC) strategy whose main feature is to use the system MLD model to predict the future evolution of the hybrid system states within a fixed prediction horizon.

The main contribution of this paper is to propose a new damper with multi-stage adjustable damping characteristics and to show how both the missions of modeling and optimal control of vehicle semi-active air suspension system with the new damper can be effectively solved by resorting to hybrid systems theory. On the basis of fluid mechanics and thermodynamic theories, the mechanism model of the air suspension system with the new damper is constructed. Since the mechanism model shows nonlinear characteristics, which can't be dealt with directly by the MLD framework, further linearization of the model and approximation of the damping characteristics are conducted. Then, the system MLD model is established through the compilation of HYSDEL. Based on the resulting hybrid dynamical model, the vehicle semi-active air suspension control problem is recast as a hybrid MPC problem. By solving a mixed-integer quadratic programming problem in simulations, the hybrid MPC controller is tuned online. Simulation results show the effectiveness and reliability of the proposed control method finally.

The rest of this paper is organized as follows. The target vehicle semi-active air suspension system with the new damper is described in Section 2. In Section 3, the system mechanism model is established, and on this basis, the system MLD model is derived through the compilation of HYSDEL. Section 4 shows how to recast the switching sequences optimization problem of the damping modes by considering the suspension performance requirements in a hybrid MPC scheme. In Section 5, numerical simulations results are presented to show the actual performance of the proposed controller. Finally, the conclusions are given in Section 6.

2. System description and analysis

2.1. System description

The general layout of the target semi-active air suspension system with damping multi-mode switching damper can be seen in Fig. 1. It is evident from the figure that the system consists of an air spring (11) and a conventional monotube hydraulic damper that is made up of a piston rod (9), three chambers, i.e. the rebound chamber (10), the compression chamber (3) and the air chamber (1), two hydraulic valves on the piston (7), i.e. the rebound valve (6) and the compression valve (8), a floating piston (2) and a damping adjustment actuator. The actuator contains six hydraulic valves, two of them (s_1, s_2) are on-off solenoid valves, which decide the oil flow path in the actuator, and four of them are check valves (*a*, *b*, *c*, *d*). The geometry of the two on-off solenoid valves are identical. To achieve four different damping modes, each check valve has an own pressure losses for the oil flow. Concretely speaking, the hydraulic oil flow pressure loss of check valve *a* is greater than that of check valve *b*, while the oil flow pressure loss of check valve *c* is less than that of check valve *d*. This structure ensures multi-stage adjustable damping characteristics by just controlling the on-off statuses of two solenoid valves, which are the core component of the damping adjustment actuator.