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Optimization and static output-feedback control for half-car active suspensions with constrained information

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ABSTRACT

In this paper, the static output-feedback control problem of active suspension systems with information structure constraints is investigated. In order to simultaneously improve the ride comfort and stability, a half car model is used. Other constraints such as suspension deflection, actuator saturation, and controller constrained information are also considered. A novel static output-feedback design method based on the variable substitution is employed in the controller design. A single-step linear matrix inequality (LMI) optimization problem is solved to derive the initial feasible solution with a sparsity constraint. The initial infeasibility issue of the static output-feedback is resolved by using state-feedback information. Specifically, an optimization algorithm is proposed to search for less conservative results based on the feasible controller gain matrix. Finally, the validity of the designed controller for different road profiles is illustrated through numerical examples. The simulation results indicate that the optimized static output-feedback controller can achieve better suspension performances when compared with the feasible static output-feedback controller.

1. Introduction

Active suspension systems are required to attenuate the vibration transmitted from the road surface interference to the car body, and to ensure the time-domain constraint conditions including suspension dynamic travel and road holding property [1]. In order to improve the performance of automotive suspension, several researchers have devoted considerable efforts to study the various types of control strategies, such as passive control, semi-active control, and active control. Recent developments have witnessed the application of the semi-active suspension to most of the high-performance automobiles due to its advantages including low energy consumption, and low cost. However, passive or semi-active vehicle suspension has a limited capacity to deal with these demands. Although, active suspension is not popular currently, it has significant development prospects due to its considerable advantages in performance.

Recently, many advanced active control strategies were proposed by using various control theories such as sliding mode control [2,3], adaptive control [4–6], fuzzy control [7,8], backstepping control [9,10], neural network control [11], and nonlinear tracking control based on ESO [12]. Particularly, H_∞ control is an effective method to realize multi-objective optimization of suspension systems. In recent years, this method has drawn the attention of several researchers [13–28]. For example, the H_∞ control problem for active suspension systems with input delays was investigated [15–20]. The H_∞

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control problem for uncertain active suspension under non-stationary running was studied [21]. Gao et al. [22] proposed a load-dependent controller for an uncertain parameter suspension system based on parameter-dependent Lyapunov functions. The finite frequency H_∞ control problem for quarter-car suspension was investigated [23–26]. H_∞ control with a wheelbase preview of a half-car model was introduced from the multi-objective control viewpoint [27,28]. The application of the H_∞ control method reduces the magnitude of sprung acceleration and ensures the relevant time-domain hard constraint conditions. This has realized the tradeoff of the suspension properties to a certain degree. This method has a certain robustness and is easy to implement.

Static output-feedback control has always attracted considerable attention due to its simple structure and ease of practical implementation [29]. When compared with state-feedback control, it is difficult to solve the static output-feedback gain matrix through the direct application of LMI technology. This is because it requires an iterative LMI method, which makes solving and programming more complicated. In recent years, there were important developments in solving the static output feedback controller through the non-iterative method. A novel LMI method was proposed to directly solve the static output feedback controller, but the method contained a number of equality constraints that significantly restricted its application [30]. A two-stage method for solving the static output feedback controller was adopted and applied to the vibration control of a building structure, but it was difficult to find an effective and feasible solution for the suspension control problem [31]. Karimi et al. [32] suggested a simple variable substitution method, which could directly solve the static output feedback gain matrix by taking the structural constraints of the controller into account. However, this method required the selection of an arbitrary matrix **L** prior to its implementation, and the selection of matrix **L** had a crucial impact on the feasibility and performance of the method. To solve this problem, Palacios-Quiñonero et al. [33] presented a two-step design method to deal with the **L** selection problem. Recently, the static output feedback control method that considered the controller structure constraints, was applied to the building structure and wind turbine control [34,35]. However, there is limited research on automotive active suspension static output feedback control that considers the constraints of the controller structure.

Based on these fore-mentioned considerations, the paper studies the static output feedback control problem for the half-car active suspension system with controller constrained information. In addition to improving the ride comfort, it also consider other constraint performances of the suspension system, such as the suspension dynamic travel and road holding. The static output-feedback control gain matrix can be directly solved with the variable substitution and LMI method. Since an additional inequality constraint is considered when solving the LMI optimization problem, it is difficult for the calculated static output feedback controller to obtain better control performance. Therefore, based on the two-step design method, a new optimization method is proposed to search for a better and more feasible solution. Finally, the effectiveness of the proposed control method is validated through numerical examples.

This paper is organized as follows. Section 2 establishes a half-car model with active suspension and formulates the performance requirements. A static output-feedback control design method is discussed in Section 3. In Section 4, simulation results are provided to demonstrate the usefulness and advantages of the designed controller. The conclusions are given in Section 5.

Notation: In this paper, the matrices $\mathbf{A}^T$, $\mathbf{A}^{-1}$ and $\mathbf{A}^\dagger$ indicate transposition, inverse and Moore–Penrose pseudo-inverse of $\mathbf{A}$, respectively. $\text{sym}(\mathbf{A}) = \mathbf{A} + \mathbf{A}^T$, $\{\mathbf{A}\}_i$ denotes the ith line of the matrix $\mathbf{A}$. The notation $*$ in matrix represents a term that is induced by symmetry. The space of the square-integrable vector functions over $[0, \infty)$ is denoted by $l_2[0, \infty)$.

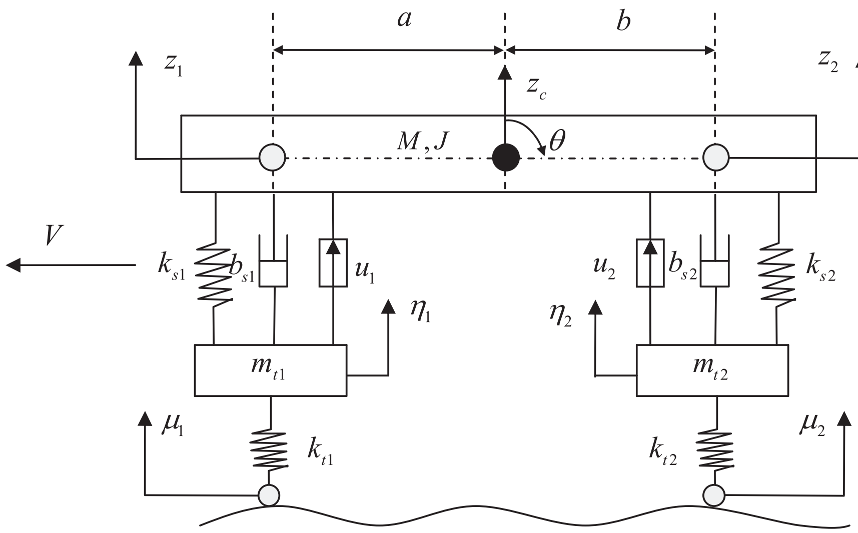

Fig. 1. The half-car active suspension model.