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A novel semi-active control strategy based on the quantitative feedback theory for a vehicle suspension system with magneto-rheological damper saturation☆

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ABSTRACT

This paper presents a robust controller for a semi-active suspension system with actuator saturation. It addresses the vehicle vibration attenuation problem under two cases: (i) without actuator fault (magneto-rheological (MR) damper) and (ii) with base oil leakage in MR damper. The solution is obtained using the quantitative feedback theory (QFT) design. The actuator (MR damper) dynamics is well approximated by a first order model with an uncertain time constant. The superior performance of the proposed QFT controller, for fault free case, is compared with the sky-hook, H_∞ control and passive suspension in time as well as in frequency domains. To address the system with faulty MR damper, a multiple model approach based QFT design is then proposed. The multiplicative type fault is considered as an MR damper fault and the faulty damper output delivering capability is then reduced by 80% to 75% due to the oil leakage in the damper. The proposed idea is centered on dividing the large uncertain system into a set of small uncertain linear system and then design the QFT controller corresponding to each of the generated linear models. The global controller is formulated by aggregating the local controller with the gap metric based weights. This new approach produces the similar performance as that of the passive fault tolerant control (FTC)-QFT design with less control effort. Extensive comparative simulations are provided to show the efficacy of the proposed method over passive FTC-QFT, passive FTC-H_∞ design and sky-hook control.

1. Introduction

The design of vehicle suspension systems has drawn considerable attention from the industrial and academic researchers in the automotive field due to its potential to improve the ride comfort, road holding and safety of passengers. In the past decades, three types of vehicle suspensions were investigated such as passive suspension, semi-active suspension and active suspension, respectively [1–7]. Passive suspension, consists of springs and dampers, provides design simplicity, cost effectiveness but effective only in a certain frequency range. The passive dampers are tuned once during the design and construction not allowing for further changes in response to a different input which limits the performances. Active suspensions can improve the performances by adding or dissipating the energy from the system using extra actuators. Thus, active suspensions require higher energy demand and cost which prevents this technique from being used in practice. Hence, in the industry, semi-active suspensions are often preferred since they can achieve desirable performance than passive suspension, and consume less power, low cost than that of active suspensions [1,5,7]. Recently, semi-active suspension system uses electro-rheological (ER) or magneto-rheological (MR) dampers to provide the controllable damping force [1,3,4,7,8] and some passenger vehicles with MR damper suspension are running on the road in practice.

As far as the application of semi-active suspension is concerned, it has been applied over a wide range of practical systems such as road vehicle suspension, seat suspension, lateral suspensions in high speed trains, landing gears in aircraft, suspensions of appliances (such as washing machines), architectural suspensions (building, bridges), and etc. [9]. This paper focuses on road vehicle suspension. Suspension systems are one of the most important and critical components of a vehicle. Suspension design and its control are the two mainstream research activities which have been undergoing in the automotive sector. This work mainly focuses on the development of control method using a robust control known as quantitative feedback theory (QFT). In the

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literature, there exist a large number of control methodologies for semi-active suspension systems. To name a few, the most famous one is the skyhook control strategy. The two state skyhook control is an on/off strategy that switches between the maximum and minimum damping coefficients depend upon the motion of suspension travel in order to achieve body comfort specifications [5,10]. The skyhook control is extended in to different forms such as modified skyhook control [11], skyhook-acceleration driven damping (SH-ADD) control [9] and skyhook-power driven damping (SH-PDD) control [12].

Two step controller design procedure for the semi-active suspension system (treated as a bilinear system) is proposed in [13]. The first step involves quasi-linearization wherein the hypothetical damping coefficient value is chosen in order to have less damping/large resonance peak with better vibration attenuation in the low frequency range. And the second step is a frequency shaping using the H_∞ optimization to attenuate the oscillation in the high frequency. The frequency shaping is used in conjunction with a sliding mode controller wherein the sliding surface is designed based on the H_∞ optimization. Semi-active H_∞ control of vehicle suspension system is proposed in [1,4]. In [4], the H_∞ controller is designed using the frequency loop shaping with ER damper being considered as a first order system. The time constant of the ER damper is also considered as an uncertain apart from the sprung mass uncertainty. In [1], the MR damper dynamics is modeled using the polynomial method proposed by [14] and the static output feedback H_∞ controller is designed using the genetic algorithm. Model predictive control (MPC) based semi-active control is also available in the literature. For example, in [15], a ”fast” optimization procedure is proposed to achieve better performances compared to the skyhook and linear quadratic (LQ) clipped approaches. Hybrid MPC is introduced in [16], wherein a hybrid controller is switched between a large number of controllers and requires a full state measurement. But, these approaches require full state measurement and a good knowledge of the model parameters. Linear parameter varying (LPV) technique is recently introduced for semi-active suspension control in [5]. The idea is to add control (designed using LPV/ H_∞ control synthesis) when the required force is in the allowed force/deflection speed space. Otherwise, rely on the passive law when the forces are outside the allowable space. In other words, the control law aims at increasing/decreasing the damping coefficient in order to keep the control signal in the semi-active quadrants. The above discussed methods do not consider both actuator saturation and the MR damper fault while in the controller design stage. This motivates us to develop a new control method to address both saturation and the damper fault using the QFT principles. Recently, the scheduling strategy based on the difference between the computed force and the achievable one is used for implementation and the LPV based semi-active system with input saturation is discussed in [17].

As far as the application of QFT to vehicle suspension system is concerned, very few works are available in the literature. For instance, a cascade QFT design for the active suspension of an off-road high mobility tracked vehicle is proposed in [6]. The approach starts with the linearization of the nonlinear model with respect to its harmonics responses, yielding generalized describing functions (GDF) in the form of amplitude and frequency dependent function values to define the plant templates. Next, the cascade QFT design takes place “from the outside to the inside” fashion. Here, the outer loop is the vertical acceleration and the inner loop is the relative angle between the road arm angle and horizontal axis (passing through road arm). The performance of the H_∞ control and QFT control are compared in [18] for the active suspension system. They showed that the vertical body acceleration of the QFT based design is lower than the H_∞ control. And with actuator dynamics, the QFT performance was comparable to the H_∞ counterpart. The first work on QFT design approach to semi-active suspension control is reported in [7]. The main idea is to consider the nonlinear MR damper dynamics as a linear uncertain system (similar to the Bingham model) in the QFT design. So the overall uncertain system is represented as a suspension system with linear uncertain MR dynamics. The comparison between the back-stepping approach and QFT control is shown under different performance indices. The performance of QFT design was better than the back-stepping design for some performance indices and comparable to that of the back-stepping counterpart for the rest. In the automotive industry, it is necessary to design control systems that consider features of safety and fault tolerant in order to improve the system reliability. The above mentioned approaches have better performance in comfort than a passive suspension but none of them consider the inherent fault in process instrumentation. Fault tolerant control (FTC) in a semi-active suspension is a relatively new area. In general, two main groups of FTC classifications are passive FTC (offline designed using the robust control with respect to possible faults) and an active one (online reconfiguration mechanism). For instance, FTC based LPV control is proposed to guarantee the performance of a vehicle model subject to actuator and sensor faults [19]. Active FTC based LPV controller with scheduling strategy is proposed in [20] with a sensor fault. And the LPV design with actuator (damper) fault case is reported in [21,22].

In the vehicle suspension with controllable dampers, one of the significant issues to be resolved is to prevent the base oil leakage from MR damper for reliable control performances such as ride comfort and road holding. However, it is not trivial in the manufacturing process and hence the performance degradation due to the oil leakage needs to be overcome by the control strategy. The base oil leakage in MR dampers creates the fault which in turn limits the damping force capability. In order to treat this issue, a new control strategy for the semi-active vehicle suspension is developed in this work. The challenges and technical contributions associated with this specific control problem are summarized as follows:

1. Proposed a QFT based semi-active suspension control strategy and extended it to a faulty situation (oil leakage in MR damper).
2. Actuator (MR damper) dynamics and its saturation problem is considered in the design strategy. Here, the actuator saturation constraint is converted into bounds on the Nichols chart for QFT design using the describing function approach.
3. For faulty case: The multiple model approach is introduced to address the FTC problem. The idea is to design the set of local linear controllers based on the linear model banks. And apply the weighted average of the local linear controller, known as global control, to the system. To the best of authors knowledge, this is the first kind of work on QFT based FTC.
4. The effectiveness of the proposed QFT approach is compared with the skyhook and H_∞ control for two cases, i.e., fault free and faulty case. It is found to deliver better performance (ride comfort, road holding) and achieves smaller root mean square (RMS) value of acceleration, tyre deflection. And smaller peak value in the power spectral density (PSD) of acceleration (over 4–8 Hz) as compared to the skyhook, H_∞ control (full uncertainty QFT design for faulty case).

The remainder of this paper is structured as follows. We first give some preliminaries in Section 2 related to the MR damper and the quarter car suspension model followed by the brief introduction to QFT. We then state the problem statement in Section 3. Next, the important components required for the proposed control method are described in Section 4. The proposed control strategy is explained in Section 5. Finally, the case study of the proposed method on quarter car suspension system is conducted in Section 6. The outcome of the case study is drawn as a conclusion in Section 7.

2. Preliminaries

2.1. MR damper dynamics

The application of MR damper to the semi-active suspension control