Mechanical Systems and Signal Processing 105 (2018) 447–466

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A new fuzzy-disturbance observer-enhanced sliding controller for vibration control of a train-car suspension with magneto-rheological dampers

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ARTICLE INFO

Article history:
Received 3 August 2017
Received in revised form 7 November 2017
Accepted 14 December 2017

Keywords:
Adaptive sliding mode control
Fuzzy sliding mode control
Magneto-rheological damper (MRD)
MRD train-car suspension
Optimal fuzzy disturbance observer

ABSTRACT

Semi-active train-car suspensions are always impacted negatively by uncertainty and disturbance (UAD). In order to deal with this, we propose a novel optimal fuzzy disturbance observer-enhanced sliding mode controller (FDO-SMC) for magneto-rheological damper (MRD)-based semi-active train-car suspensions subjected to UAD whose variability rate may be high but bounded. The two main parts of the FDO-SMC are an adaptive sliding mode controller (ad-SMC) and an optimal fuzzy disturbance observer (op-FDO). As the first step, the initial structures of the sliding mode controller (SMC) and disturbance observer (DO) are built. Adaptive update laws for the SMC and DO are then set up synchronously via Lyapunov stability analysis. Subsequently, an optimal fuzzy system (op-FS) is designed to fully implement a parameter constraint mechanism so as to guarantee the system stability converging to the desired state even if the UAD variability rate increases in a given range. As a result, both the ad-SMC and op-FDO are formulated. It is shown from the comparative work with existing controllers that the proposed method provides the best vibration control capability with relatively low consumed power.

1. Introduction

With essential advantages, MRD has been widely applied in practice including road vehicles or train cars [1–10] or in civil engineering [11–15]. In this work, we pay attention to the first group related to MRD-based semi-active train-car suspensions. Reality shows that the effectiveness of these systems is always impacted negatively by UAD. UAD may come from

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Abbreviations: MRD, magneto-rheological damper; i-MRD, inverse MRD; UAD, uncertainty and disturbance; SMC, sliding mode controller; DO, disturbance observer; FDO, fuzzy disturbance observer; FDO-SMC, FDO enhanced sliding mode controller; ad-SMC, adaptive sliding mode controller; op-FDO, optimal fuzzy disturbance observer; op-FS, optimal fuzzy system; SMCT, sliding mode control technique; FL, fuzzy logic; FSMC, fuzzy sliding mode controller; ANFIS, adaptive neuro-fuzzy inference system; ANFIS-I-MRD, ANFIS inverse MRD; Rank-DE, rank differential evolution; MISO, multi-input and single output; NFSmUoC, neuro-fuzzy sliding mode control enhanced by an uncertainty observer; FPSC, fuzzy-based predicting sliding controller; AFSM, adaptive fuzzy sliding mode controller.

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https://doi.org/10.1016/j.ymssp.2017.12.019

the lack of accuracy of the measurement devices, the model errors and the unknown influence of environment on the systems. Besides, the change in the physical properties of magneto-rheological fluids due to the temperature variability is also a main cause of UAD. Operating in this condition, an adaptive control strategy needs to be set up to improve control quality. For this aim, various solutions have been proposed. For example, sliding mode control technique (SMCT) [2–6,16–18], optimal and adaptive control [19–22], artificial neural networks, fuzzy logic (FL) [7,8,11,23,24], and the combination [9,25–29] have been considered as useful control tools. With the crucial advantages such as the simplicity in implementation, the capability to deal with UAD, and being facile to combine with other mathematical tools, SMCT has been applied effectively to several fields [2–5,17,30–32].

To exploit SMCT, a control strategy must be deployed to enforce system's dynamic response towards the sliding surface in the approaching phase and uphold the switching along it in the sliding phase stably [4,5,32]. During the operating process, the controller must adjust the sliding mode parameters adaptively to get fast system's convergence. This, however, sometimes causes unwanted chattering problem which is understood as the change of control signal with high frequency and large amplitude-varying rate [33]. This phenomenon deteriorates the control quality and may results in damage to the hardware system [4,30,32]. The ability to reach to the sliding surface and keep system states on that surface stably without chattering reflects the quality of sliding mode control systems. For this aim, there have been many researchers to be prone to appropriate combinations of SMCT and FL in the form called fuzzy sliding mode control (FSMC). In the model, the FL can provide useful solutions for function approximation with a high degree of flexibility along with vigorous tools for information inference [5,8,34]; while the SMCT can create adaptive control laws based on stability analysis [17,18]. Such combined advantages have been efficiently exploited in many applications [4,12,26–28,35–37]. In this tendency, optimization methods are often utilized to improve the system performance [38,39]. Together with the advantages, FSMC, however, may increase the time delay due to the high calculating cost in some cases [34]. Although the fuzzy gains adopted in [36,37] were becoming to stamp out the chattering status, these resulted in expanding time delay. For real-time control systems such as the ones for high speed trains, this aspect should be paid attention.

In [12], Suresh and Wen presented solutions for establishing the gain of SMC based on FL to avoid the chattering status. Depending on the required boundary thickness for the sliding surface, a fuzzy system was built to determine the fuzzy switching gain. Using this method, a smooth switching near the zero vicinity to improve SMC's ability can set up. However, if the system is influenced by UAD with high intensity, the chattering problem is difficult to avoid since the sliding surface is forced into the vicinity of the boundary layers continuously. Thus, the fuzzy system may not estimate fully system's dynamic response to establish an appropriate control signal. Moreover, the calculating cost relative to the fuzzy gain is another disadvantage in the case of real-time control process. In [35], an adaptive control strategy for a class of nonlinear systems subjected to UAD was presented. To depict the boundaries of un-modeled dynamics, a feedback linearization approach was used. In addition, to relax the norm-bounded constrains on the control law and solve the chattering problem, a fuzzy inference mechanism was combined with the adaptive controller. Another combination type constituted of SMC, FL and DO can be found in [4], in which a SMCT-based controller for the train-car MRD suspension subjected to UAD has been conducted. In this work, in order to compensate for uncertainty a FL in the form of an adaptive neuro-fuzzy inference system (ANFIS) was used; while a DO was implemented to take account for the external disturbance. There is, however, a difficulty related to the variability of the UAD since control effect is sensitive to the time-varying rate of UAD. Moreover, this control system lacks a becoming constraint mechanism to update the SMC and DO.

For the control of MRD-based semi-active train-car suspensions subjected to UAD whose time-varying rate may be high but bounded, it is understood that SMC appropriately associated with DO and FL is a suitable option. However, in this operating condition the following issues need to be addressed to reach to the aim.

(1) Due to the variability of UAD, the adaptive ability must be established for both the DO and SMC. A conflict between the update laws of the DO and SMC may happen if two processes lack a becoming constraint mechanism. In other words, an update law can make the DO convergent, while it may cause unstable status of the SMC, or conversely. In order to avoid this trap, what are the required constraints to guarantee the stable convergence even if the UAD variability rate increases in a given range?
(2) The FL can bring the control system essential advantages together with the arisen disadvantages. The question is how to exploit the ability of FL to infer information and approximate functions without the considerable calculating-cost arising.

Inspired by controlling vibration of MRD-based semi-active train-car suspensions subjected to UAD whose time-varying rate may be high but bounded, in this work we propose a novel optimal fuzzy disturbance observer-enhanced sliding mode controller named FDO-SMC for this object. The FDO-SMC is constituted of an adaptive sliding mode controller ad-SMC, an optimal fuzzy disturbance observer op-FDO, and an inverse MRD model based on an ANFIS named ANFIS-I-MRD. First, initial structures of the SMC and DO are established together with their adaptive update laws which are relied on Lyapunov stability analysis associated with a proposed parameter constraint mechanism. An optimal fuzzy system (op-FS) is designed to fully implement the constraint mechanism. The role of this phase is to guarantee the stable convergence to desired states even if the UAD variability rate increases. As a result, the ad-SMC and op-FDO are created to estimate control force. The ANFIS-I-MRD then specifies current value supporting the MRD to generate the estimated requiring damping force for stamping out unwanted vibration. Consequently, three main technical contributions of this work are summarized as follows. The