Mechanical Systems and Signal Processing 117 (2019) 667–688

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Practical multi-objective control for automotive semi-active suspension system with nonlinear hydraulic adjustable damper

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ARTICLE INFO

Article history:
Received 2 May 2018
Received in revised form 2 August 2018
Accepted 6 August 2018

Keywords:
Semi-active suspension
Multi-objective control
Damper control
Sliding mode control
Particle swarm optimization
Neural network

ABSTRACT

In recent, the development of the automotive semi-active suspension (SAS) system with the nonlinear hydraulic adjustable damper (HAD) has attracted widely attention due to its superiorities of low energy consumption, fast response, durable, reliable and simple structure. Many existing SAS researches focus on control algorithms for limited objectives and assume the control signal is the damping force, but very few of them discusses how to realize the calculated damping force. To solve this problem, the unknown regulating mechanism of the nonlinear HAD should be modeled and a complex multi-objective control of the SAS system should be designed. Aiming at modeling the regulating mechanism of the nonlinear HAD, this work constructs a novel compensation system by using fuzzy neural network or grey neural network algorithm in order to realize the desired damping force by regulating the stepper motor angle adaptively. Meanwhile, a new multi-objective control strategy, particle swarm optimization based sliding mode control method, is originally proposed to calculate the desired damping force to achieve exact damping force control of the SAS system. To realize the practical application of the SAS system with the nonlinear HAD, an online hardware-in-the-loop test is conducted on a quarter car test rig. Numerical and experimental results illustrate that the modeled regulating mechanism of the nonlinear HAD and the proposed multi-objective control of SAS system are effective to improve the vertical performance of the vehicle and feasible in practical applications.

1. Introduction

In recent, increasing demand of the vehicle performance promotes the development of automotive suspension systems, while the type of the suspension system is a crucial issue that mainly affects the performance of the vehicle [1–3]. There are three types of vehicle suspension systems, namely, passive suspension, semi-active suspension (SAS) and fully active suspension. The passive suspension has a simple structure with conventional steel spring and linear viscous damper. However, it cannot meet the high-level requirement of vehicle performance as the spring stiffness and the damper coefficient are fixed. To improve the vehicle performance, the controllable suspension systems (i.e. the SAS and the active suspension) have been widely used due to their flexibility in improving the vehicle performance [4–7]. Compared with the active type, the SAS system becomes a favorable choice with less power consumption, low cost and consideration of less parameter [8–10]. A SAS system usually refers to the damping force control in which an adjustable damper is often considered [11,12]. As for

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https://doi.org/10.1016/j.ymssp.2018.08.022
0888-3270/

the adjustable damper, the nonlinear hydraulic adjustable damper (HAD) using hydraulic flow adjustment method is the most popular in the automotive industry with less power consumption, fast response, durable, reliable and simple structure [13,14]. Hence, this research focuses on the SAS system with a nonlinear HAD. In this system, the desired damping force can be calculated by developing a control strategy and realized by adjusting the nonlinear HAD.

The HAD is a nonlinear device to provide the desired damping force, while the damping force of HAD is related to damping level, piston displacement, piston speed, and temperature of the hydraulic oil. Moreover, the damping coefficient changes according to various driving conditions, which also increases the nonlinearities of the proposed HAD and makes it difficult to match the control signal produced by the controller. In existing SAS researches, an assumption is made that the control signal is the damping force and very few researcher discusses how to realize the damping force. This impedes the practical application of the nonlinear HAD in automobiles. To solve this practical problem, the regulating mechanism of the nonlinear HAD should be modeled accurately to adjust the nonlinear HAD according to the desired damping force. Based on the general theory of dampers, the damping force of the nonlinear HAD varies along with the damping level (i.e. stepper motor angle), piston displacement, piston speed, and temperature of hydraulic oil. This regulating mechanism is difficult to be modeled due to multiple variables and complicated relationship. Generally, the conventional look-up table method is suitable for three-dimensional problem, while there are five variables in the modeling of the regulating mechanism. It is quite difficult to construct a five-dimensional look-up table to obtain the required motor angle. To solve this problem, an additional compensation system to compensate the influence on the damping force by multi-variables should be developed to achieve the desired damping force at different working conditions by automatically regulating the motor angle.

To construct the compensation system, an effective algorithm should be selected for the nonlinear HAD to rapidly determine the required motor angle. In existing literatures, some investigations have been done on establishing the regulating mechanism of dampers via neural networks. A neural network based black-box model was built for the hydraulic damper to implicitly describe the relationship between damping force and adjustable valve based on sample experimental data [13]. However, plenty of weights should be optimized and hence heavy computational cost and many training data are required. Therefore, a new neural network should be investigated to construct the compensation system for the nonlinear HAD.

To ensure the accuracy and decrease the computational cost, the artificial neural network can be modified based on the characteristics of the nonlinear HAD. The characteristic data of the nonlinear HAD can be obtained from experiments. Though these complex characteristic data can provide some priori knowledge, it is difficult to collect numerous data from experiments in a short damper working cycle. To this end, a fuzzy method is employed as it works well with a simple reasoning process based on the priori knowledge. The fuzzy method requires less number of training data and does not require an explicit model [15,16]. By combining the advances of fuzzy theory and neural network method, a fuzzy neural network (FNN) is formed to construct the compensation system with multiple variables.

The nature of the fuzzy logic algorithm determines that the FNN can work well with complex characteristics and less training data based on existing prior knowledge. However, some variables in this study are time-dependent and FNN may not be the best choice. Motivated by the recent fact that a grey model (GM) was successfully applied to time-dependent variables with less number of training data (at least 4 sets of training data) [17], a grey neural network (GNN) is also proposed in this study as an alternative solution and comparative case. As a result, by respectively using the FNN algorithm and GNN algorithm, two compensation systems are individually constructed to model the regulating mechanism of the nonlinear HAD to realize the desired damping force by regulating motor angle adaptively. By comparing the performance of the two individual compensation systems, the better algorithm can be determined to model the regulating mechanism for damping force control, and then applied to realize the desired damping force in practical application.

For the practical application to the SAS system, the desired damping force is calculated by a control strategy. In existing literatures, various classical control strategies are available for the SAS system, such as skyhook control [18], adaptive control [19], optimal control [20], proportional-integral-derivative control [21,22], ground-hook control [23], hybrid control [24], and robust control [25]. However, the aforesaid classical control strategies mainly focus on the improvement of the ride comfort, and were proved that they could not satisfy the requirement of multi-objective control on vehicle dynamics [8,18,26,27]. Moreover, the control of the basic suspension performance indices is a multi-objective control problem since the function of the SAS system is to provide the competent ride comfort, road holding capacity and suspension supporting ability. In the multi-objective control problem, conflicts and compromises among the suspension basic functions should be carefully considered. Besides, the control strategy is one of critical factors to affect the vehicle characteristics in reality. Therefore, this work tries to design a multi-objective control strategy for the SAS system.

As for the multi-objective control strategy in the SAS system, both the linear quadratic regulator (LQR) method and sliding model control (SMC) were successfully applied to optimize the overall suspension performance in the past few years. LQR behaves well in the compromised nonlinear or uncertain system control of the suspension system with different weights [28]. However, a local optimum is usually suffered when employing this method in global optimal control of the suspension system. Regarding the SMC method, it is an effective robust control approach with fast response and good transient performance. Moreover, by using the SMC method, a more comprehensive improvement in vehicle dynamic performance could be obtained [29,30]. As this research focuses on the multi-objective control of SAS system, SMC method is considered. However, an appropriate switching surface should be well-designed to optimize the overall suspension performance in developing the SMC controller for the SAS system. This is because the switching surface greatly influences the dynamic performance of the controller [31]. So an additional optimization method is preferable to communicate with the SMC part and solves the