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A hybrid clustering based fuzzy structure for vibration control – Part 2: An application to semi-active vehicle seat-suspension system

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ABSTRACT

This work presents a novel neuro-fuzzy controller (NFC) for car-driver's seat-suspension system featuring magnetorheological (MR) dampers. The NFC is built based on the algorithm for building adaptive neuro-fuzzy inference systems (ANFISs) named B-ANFIS, which has been developed in Part 1, and fuzzy logic inference systems (FISs). In order to create the NFC, the following steps are performed. Firstly, a control strategy based on a ride-comfort-oriented tendency (RCOT) is established. Subsequently, optimal FISs are built based on a genetic algorithm (GA) to estimate the desired damping force that satisfies the RCOT corresponding to the road status at each time. The B-ANFIS is then used to build ANFISs for inverse dynamic models of the suspension system (I-ANFIS). Based on the FISs, the desired force values are calculated according to the status of road at each time. The corresponding exciting current value to be applied to the MR damper is then determined by the I-ANFIS. In order to validate the effectiveness of the developed neuro-fuzzy controller, control performances of the seat-suspension systems featuring MR dampers are evaluated under different road conditions. In addition, a comparative work between conventional skyhook controller and the proposed NFC is undertaken in order to demonstrate superior control performances of the proposed methodology.

1. Introduction

Vehicle seat-suspension systems play a significant role in improving ride-comfort performance of vehicles. In general, vibration control of seat-suspension systems can be classified into three approaches: the passive, active and semi-active vibration control method. A passive vibration-control unit consists of a resilient member (stiffness) and an energy dissipater (damper) to either absorb vibratory energy or load the transmission path of the disturbing vibration. Reality shows that passive control is quite simple and cheap. However, this configuration has significant limitations in systems where broadband disturbances of highly uncertain nature are encountered. In addition, the passive seat-suspension systems may cause an amplification of vibration at frequencies close to natural resonance frequencies of the systems, which are usually

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List of Symbols

c_s, c_v, c_t	passive damping coefficients
c_{sm}, c_{vm}	semi-active damping coefficients of MR dampers
d	relative displacement of MR damper piston
$f_{MR}^{(.)}$	damping force of the MR damper (.)
$f_{MR\_FIS}^{(.)}$	desired values of $f_{MR}^{(.)}$ estimated based on FIS
$I_i^{(.)}$	current intensity
J	fitness function
k_s, k_v	stiffness coefficients of linear springs
k_t	tire deflection stiffness
m_s	mass of seat, including mass of the human body
m_v, m_t	mass of vehicle and tire
$v_{(.)}$	velocity of MR damper piston
z_s, z_v, z_t	vertical displacements of m_s, m_v, m_t
z_r	vertical road displacement

between 1 and 2 Hz [1]. In order to compensate for these limitations, active vibration-control systems are utilized. With an additional active force introduced as a part of an active suspension unit, the vibration-control system is then controlled using different algorithms to make it more responsive to sources of disturbance. Although, the active system can provide high control performance in a wide frequency range, it is not widely utilized due to complex structure, large power requirement, and high cost of manufacturing and operating. Semi-active configuration resolves these limitations by effectively integrating a tuning control scheme with tunable passive devices. For this, active force generators in the active suspension system are replaced by modulated variable compartments such as variable rate damper and stiffness. Therefore, the semi-active suspension can offer desirable performance without requiring large power sources and expensive hardware. With these strong points, the semi-active suspension systems have received many attentions in automotive applications. This tendency is more clearly manifested when controllable dampers, such as magnetorheological (MR) one, are commercially used [2]. It is shown that semi-active suspension systems featuring MR dampers (MR damper suspension systems in short) have inherent several advantages such as simple structure, small number of mobile components, and noise-free fast operation [3]. In addition, semi-active MR suspension systems consume much less power than power consuming of active suspensions [4]. It is noted that in the controllers for MR damper seat-suspension systems, a harmonious combination between an electronic control system and a mechanical system should be achieved. In order to determine the control input for MR damper, dynamic response of the suspension systems such as displacement, velocity or acceleration signals need to be measured and an appropriate control strategy should be employed. The control input, which is the applied current for MR dampers, is calculated such that controlled signals are adjusted to satisfy given controlling targets. In this study, a ride-comfort-oriented tendency (RCOT) is applied and the applied current should be properly set to significantly reduce vertical acceleration of the driver. In addition, the ability of road holding is also considered as second requirement of the suspension control system. It is noted that reality shows the hysteretic dynamic response and high nonlinear characteristics of MR dampers. It is a multi-dimension relationship of damping force on exciting frequency, acceleration, velocity, displacement, current, etcetera [5]. Therefore, nonlinear control systems such as ones built based on neural networks (NN), fuzzy logic (FL) have received many attentions in controller design of MR suspension systems [6,7].

FL is an innovation approach for building solution to multi-parameter and nonlinear control problems. In controllers built based on this approach, instead of using transfer functions which are mathematical models for explicitly expressing the systems, human experience and experimental results are rather used for definition of control strategies [8,9]. By using this way for complicated nonlinear systems, solutions are usually offered faster and more effectively than using conventional control design techniques. It has been shown that an optimal FL system could be built based on a NN system, which is referred as the neuro-fuzzy (NF) system. In such a combination, the FL provides a strong mathematical tool to evaluate system response tendency based on perceptual and linguistic attributes associated with expert cognition or inference ability of data-driven models, while the NN provides learning, remembering and adaptive capabilities. A large class of NF approaches utilizing the NN learning ability to determine optimal structure and parameters of the fuzzy logic systems has been proposed [10–12]. It has also been shown that the NF system is more efficient and powerful than the neural network or fuzzy logic alone [10,13]. Hence, the NF has been widely used in control systems of MR damper suspension systems [6,7,14].

In Part 1 of this study, an algorithm for building adaptive neuro-fuzzy inference systems (ANFIS) named B-ANFIS has been developed. The results show that both the robustness and accuracy in system identification are significant advantages of the B-ANFIS. In this Part 2, a novel neuro-fuzzy controller (NFC) for MR damper seat-suspension systems using the B-ANFIS is to be developed. This directly indicates that the effectiveness of the B-ANFIS in the control field is evaluated through the application of NFC to the semi-active suspension system. To build the NFC, firstly, a control strategy based on RCOT is established. Subsequently, optimal FIS are built based on a generic algorithm (GA). The FISs are used to estimate the desired damping force that satisfies the RCOT corresponding to the road status at each time. The B-ANFIS is then used to build the ANFIS for inverse dynamic models of the suspension system (I-ANFIS) to determine the desired applied current. In order to demonstrate the effectiveness of the developed neuro-fuzzy controller, control performances of the MR seat-suspension systems are evaluated at several different road conditions. Both the ride-comfort and the road holding ability of vehicle tire are analyzed and presented in time domain.

2. 3-DOF Mr seat-suspension system

Focusing on the car-driver's seat-suspension system, a simplified model of the MR damper seat-suspension system integrated with the quarter-car model is depicted in Fig. 1. This is a three-degree-of-freedom suspension system (3-DOF-SS). In this model,