Journal of Sound and Vibration 431 (2018) 405–421

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Rate-independent linear damping in vehicle suspension systems

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ARTICLE INFO

Article history:
Received 12 December 2017
Received in revised form 15 May 2018
Accepted 25 May 2018

Handling Editor: D.J Wagg

Keywords:
Vehicle suspension system
Rate-independent linear damping
Semi-active control
Skyhook
Groundhook

ABSTRACT

Over the past few decades, several semi-active controllers have been proposed for vehicle suspension systems. Skyhook and groundhook controllers are well-studied and very effective in isolating vibrations. However, these controllers mitigate either the sprung or unsprung mass response at the expense of the other. Moreover, there is no sensor to directly measure the absolute velocity of components in the suspension system (and estimates are subject to error), making it challenging to implement skyhook and groundhook controllers in practical cases. To overcome these limitations, there is a need for a type of damping that mitigates both sprung and unsprung mass responses and also can be implemented using simple local sensors. This paper proposes the use of rate-independent linear damping (RILD) for vehicle suspension systems. RILD provides direct control over displacement; beneficial for low-frequency dynamic systems such as suspension systems that are subject to high frequency vibrations (relative to the system fundamental natural frequency). RILD directly attenuates displacement responses with low damping forces, producing low acceleration responses. The RILD damping force is proportional to the displacement advanced in phase $\pi/2$ radians, which makes it noncausal. In this study, a modal causal filter-based approach is proposed to mimic the ideal noncausal response of the RILD model. Acceleration measurements of the sprung mass are used with a Kalman filter to estimate the displacements needed for the algorithm. Numerical analyses were conducted to demonstrate performance of the proposed model in matching noncausal RILD responses. Additionally, the advantages of the proposed model over well-known skyhook and groundhook controllers are studied.

1. Introduction

Vibration control can be classified in three major categories, passive, active and semi-active. Passive control is practical and cost effective; however, the performance is fixed and tuned for a particular frequency range. Passive systems have inherent limitations in achieving broad performance objectives. On the other hand, active systems can be programmed to perform well under a variety of scenarios, but they are more expensive, require a constant power source, and can potentially destablize a system. As a result of the limitations of both type of systems, semi-active vibration isolation was introduced by Crosby and

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https://doi.org/10.1016/j.jsv.2018.05.037
0022-460X/

Karnopp [1,2]. These systems have the adaptable control performance of active systems coupled with the ruggedness of passive systems.

To achieve semi-active suspension, various types of controllable dampers can be used. Among those, magnetorheological dampers (MR) are popular devices since the damping force generated by these dampers can be quickly changed with a change in magnetic field. Other examples include electro-rheological dampers (ER), variable orifice dampers, and controllable fluid dampers [3].

Semi-active control has been applied to vehicle suspension systems by a number of researchers. Choi et al. [4] used skyhook semi-active control law with an ER damper. The same controller was used by Yao et al. [5] with an MR damper in the suspension. Different variations of skyhook control are investigated in detail by Ivers and Miller [6]. Shen et al. [7] investigated three semi-active controllers including: the limited relative displacement method, the modified skyhook method, and the modified Rakheja-Sankar approach for use in suspension MR damper systems. Both numerical and experimental tests were carried out and the performance of the three controllers were compared. Motovali Khiavi et al. [8] proposed a nonlinear tracking control law to track a desired skyhook damping force for a quarter car model with a MR damper.

Ahmadian and Pare [9] experimentally studied three semi-active controllers including: skyhook, groundhook, and a hybrid control policy on a quarter car vehicle model with MR damper. In this study, it was shown that increasing the skyhook damping results in better vibration performance of the sprung mass of the car at the expense of the unsprung mass responses. The reverse holds true for groundhook controller; increasing groundhook damping force results in reduction of unsprung mass responses (i.e., displacement or acceleration) and increase in sprung mass responses. Therefore, the authors proposed a hybrid control algorithm which is a linear combination of skyhook and groundhook controllers. It was concluded that a hybrid algorithm can better improve vehicle stability as well as ride comfort and have the combined benefits of skyhook and groundhook controllers. However, all variations of skyhook, groundhook, and the hybrid control policy require measurements or estimates of the absolute velocity of the sprung or unsprung mass of the vehicle.

Semi-active control has also been studied for the seismic protection of buildings. Leitmann [10] designed a semi-active control algorithm for ER dampers using Lyapunov's direct theory. Inspired by this work, Kim and Lee [11] developed a semi-active on-off control law for a multi-degree-of-freedom (MDOF) suspension system using Lagrange's equations of motion. Dyke et al. [3] used a clipped-optimal control strategy and investigated the effectiveness of MR dampers in reducing building responses over wide variety of seismic excitations. McClamroch and Gavin [12] developed a decentralized bang-bang control algorithm to control an ER damper. The method uses the Lyapunov function to represent the total vibrational energy in the structure. The authors also proposed a maximum energy dissipation semi-active control law as a variation to their decentralized bang-bang control law. Inaudi [13] devised a modulated homogenous friction semi-active control law to use with variable friction damper. Jansen and Dyke [14] conducted a comparative study on the seismic performance of control laws based on: Lyapunov's direct theory, decentralized bang-bang control, maximum energy dissipation, clipped-optimal control, and modulated homogenous friction. They concluded that despite the differences in seismic performance between various control algorithms, all semi-active control algorithms improved the seismic behavior compared to the best passive system. Moreover, they showed that the Lyapunov control algorithm, the clipped-optimal algorithm, and the modulated homogeneous friction algorithm are best suited for use with MR dampers.

A new type of damping is proposed herein for vehicle suspension systems to address the limitations of variations on skyhook and groundhook controllers. These limitations include clear tradeoffs in mitigating the vibration of one mass at the expense of the other and the need for sensors that can measure (or be used to estimate) absolute velocity. Rate-independent linear damping (RILD), also known as linear hysteretic damping, complex-value stiffness, structural damping, and solid damping [15–17] provides an attractive control alternative for low-frequency systems such as vehicle suspension system through direct control over displacement. In RILD, the restoring force is proportional to the displacement advanced in phase by $\pi/2$ radians (90°), leading to its noncausality. Keivan et al. [18] proposed a causal filter-based control algorithm to realize RILD in base isolated structures under earthquake loads. The effectiveness of the causal filter-based approach in mimicking RILD was shown in both numerical simulations and experimental shake-table tests.

In this study, a control law is proposed for a quarter car model based on RILD. A causal filter-based model for RILD is combined with the modal decomposition of the quarter car model's response. The performance of the proposed control algorithm is then compared to classic skyhook and groundhook control algorithms. Results indicate that the proposed modal causal filter-based approach (MCFB) can improve both sprung and unsprung mass responses at the same time, and therefore there is no compromise as seen in skyhook and groundhook controllers. Moreover, the only measurement needed to implement this method is the absolute acceleration of the sprung mass which can be measured using a standard accelerometer. A Kalman filter can accurately estimate all of the necessary states from this measurement. This simplicity is a great benefit for practical implementation.

In Section 2 of the paper, the equations of motion of the quarter car model are presented. Then, the theory behind the skyhook and groundhook controllers are reviewed. Next, the concept of RILD is presented, followed by the causal filter-based method (CFB) to approximate RILD. Finally, the modal causal filter-based algorithm (MCFB) is proposed in Section 2.6. In Section 3, the two different types of road profile considered in this study are presented. In Section 4, the vibrational performance of the MCFB approach is compared to that of CFB approach in mimicking RILD responses. Finally, in Section 5, the MCFB controller is compared to skyhook and groundhook controllers through numerical simulations and the advantages of this approach is shown over the two classical controllers.