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Active control of an innovative seat suspension system with acceleration measurement based friction estimation

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ABSTRACT

In this paper, an innovative active seat suspension system for vehicles is presented. This seat suspension prototype is built with two low cost actuators each of which has one rotary motor and one gear reducer. A H_∞ controller with friction compensation is designed for the seat suspension control system where the friction is estimated and compensated based on the measurement of seat acceleration. This principal aim of this research was to control the low frequency vibration transferred or amplified by the vehicle (chassis) suspension, and to maintain the passivity of the seat suspension at high frequency (isolation vibration) while taking into consideration the trade-off between the active seat suspension cost and its high frequency performance. Sinusoidal excitations of 1–4.5 Hz were applied to test the active seat suspension both when controlled and when uncontrolled and this is compared with a well-tuned passive heavy duty vehicle seat suspension. The results indicate the effectiveness of the proposed control algorithm within the tested frequencies. Further tests were conducted using the excitations generated from a quarter-car model under bump and random road profiles. The bump road tests indicate the controlled active seat suspension has good transient response performance. The Power Spectral Density (PSD) method and ISO 2631-1 standards were applied to analyse the seat suspension's acceleration under random road conditions. Although some low magnitude and high frequency noise will inevitably be introduced by the active system, the weighted-frequency Root Mean Square (RMS) acceleration shows that this may not have a large effect on ride comfort. In fact, the ride comfort is improved from being an 'a little uncomfortable' to a 'not uncomfortable' level when compared with the well-tuned passive seat suspension. This low cost active seat suspension design and the proposed controller with the easily measured feedback signals are very practical for real applications.

1. Introduction

Much research is being done on drivers' ride comfort. It is believed that the severe vibration transferred from a rough road is one of the leading factors influencing drivers' ride comfort and health [1]. Many different approaches to minimise the

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vibration felt by drivers have been proposed. Seat suspension, which is the most direct way to reduce the vibration felt by drivers, is easily modified, optimised and controlled. Thus, the main studies have aimed at optimising and controlling seat suspensions. There are three main types of seat suspension: passive, semi-active and active. Optimisations of the spring stiffness and the damping coefficient have been studied for passive seats. Passive seats can both decrease and increase vibration. Generally speaking, less spring stiffness may lead to good driver ride comfort but causes large suspension deflection and an increase in the vibration transmitted at low frequency. Deflections can sometimes reach the limit of movement. Many different approaches have been proposed to overcome this problem. Studies of nonlinear stiffness [2] and negative stiffness structures [3] for passive seats have been conducted and they show that there is a trade-off between ride comfort and suspension deflection in low frequency vibration.

In recent years, some research into semi-active seats has been conducted. Semi-active seat suspension using the electrorheological (ER) fluid damper and the magnetorheological (MR) fluid damper has been proposed [4,5]. Magnetorheological elastomers (MRE) have been introduced into seat suspensions in [6]. Sun et al. [7] propose an MRE-based isolator for the horizontal vibration reduction of a vehicle seat. Hiemenz et al. [8] apply MR dampers for helicopter crew seats to enhance occupant comfort. On the other hand, it is widely accepted that an active suspension is the most effective way to improve ride comfort and for this reason it has attracted attention in recent years. Several active seat suspension systems have been proposed with different kinds of actuators. An active seat suspension with two electromagnetic linear actuators has been designed and built [9]. An active seat suspension consisting of a hydraulic absorber and a controlled air-spring is studied in [10]. Kawana and Shimogo [11] use an electric servomotor with a ball screw mechanism as actuator for a truck seat. An active pneumatic vibration isolation system has been applied in negative stiffness structures [12].

There are many reputable control strategies for both semi-active and active seat suspensions; e.g., H_∞ control [13], linear quadratic gauss (LQG) [14,15], and adaptive control [16]. Du et al. [17] propose a direct voltage output observer based H_∞ controller with a Takagi-Sugeno fuzzy model to solve the nonlinear problem of an MR damper. Choi et al. [18] present a new adaptive fuzzy sliding mode controller. Maciejewski [19] proposes an active vibration control strategy based on a primary controller and actuator reverse dynamics.

If the seat suspension deflection is too large, it will be difficult for drivers to use their hands and feet to operate the controls such as the steering wheel and brake pedal. When this occurs, the suspension may reach its limit and ride comfort will deteriorate. This means that the trade-off between ride comfort and seat suspension deflection needs to be considered and, whether there is an active or a semi-active controller, this means that a multi-objective controller is needed. The suspension's relative displacement, seat vibration acceleration and cab floor vibration acceleration can be measured in real-time. The seat suspension controller design must consider those measureable variables as feedback for practical application.

Disturbance observers have been extensively studied in recent years [20–23]. Yang et al. propose a disturbance observer with mismatched uncertainties for sliding-mode control [23]. An extended disturbance observer for sliding mode control is proposed for further study [22]. Kim et al. present a disturbance observer for estimating higher order disturbances [24]. Friction, as a kind of disturbance, has always been ignored or considered together with system disturbances in the design of seat suspension controllers. In the cases where friction plays an important role in the controlled system, it needs to be carefully considered. Friction models and friction compensation are studied widely in high-precision servo mechanisms, hydraulic systems and robots [25]. Ray et al. propose an adaptive friction compensation method using an extended Kalman-Bucy filter for friction estimation [26]. Ruderman and Iwasaki [27,28] propose a nonlinear state observer for pre-sliding friction control and a nonlinear friction dynamics observer for motion control.

In the above-mentioned literature, direct force output actuators (such as pneumatic springs [10] and linear motors [16]) have been widely applied to active seat suspension. To overcome the drawbacks of high cost and high energy consumption, we have used an innovative active seat suspension system. Rotary motors have a lower cost than do linear motors. There have been a number of studies using a screw mechanism [11] and a rack and pinion device [29] to transform the rotary motor's torque into a vertical force. In this present research, rotary motors with gear reducers were applied as actuators which exert torque directly to the scissor structure centre of a traditional seat suspension. An acceleration measurement-based observer was designed to estimate friction. Because friction has a large effect on the system's performance, a H_∞ controller with friction compensation was developed. The proposed active vibration control approach applied feedback from seat acceleration, suspension relative displacement and suspension relative velocity which could be measured or derived from measured variables. Sinusoidal vibration and vibration signals generated from a quarter-car model under bump and random road profiles were used to test the active seat suspension system. The experimental results show that the designed seat suspension system can successfully isolate vibration from the vehicle seat.

The remainder of the paper is organised as follows; Section 2 presents the proposed active seat suspension design and identifies the parameters of the prototype, Section 3 discusses the friction observer and a H_∞ controller with friction compensation, the experimental results are presented in Section 4 and Section 5 presents the conclusions of this research.

Notation: I is used to denote the identity matrix of appropriate dimensions and * is used to represent a term that is induced by symmetry.

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