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Vehicle Suspension Systems and Electromagnetic Dampers

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Author's Declaration

I hereby declare that I am the sole author of this manuscript. To the best of my knowledge, the document contains no material previously published or written by another person except where due reference is made in the text.

Dr. Saad Kashem

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Abstract

A suspension system is an essential element of a vehicle to isolate the frame of the vehicle from road disturbances. It is required to maintain continuous contact between a vehicle's tyres and the road. In order to achieve the desired ride comfort and road handling performance, many types of research have been conducted. A new modified skyhook control strategy with an adaptive gain that dictates the vehicle's semi-active suspension system is presented. The proposed closed-loop feedback system first captures the road profile input over a certain period. Then it calculates the best possible value of the skyhook gain for the subsequent process. Meanwhile, the system is controlled according to the new modified skyhook control law using an initial or previous value of the skyhook gain. In this book, the proposed suspension system is compared with passive and three other recently reported skyhook controlled semi-active suspension systems through a virtual environment with MATLAB/Simulink as well as an experimental analysis with Quanser suspension plant. Its performances have been evaluated in terms of ride comfort and road handling performance. The model has been validated in accordance with the international standards of admissible acceleration levels ISO2631 and human vibration perception. This control strategy has also been employed on the full car model to improve the isolation of the vibration and handling performance of the road vehicle.

This book also describes the development of a new analytical full vehicle model with nine degrees of freedom, which uses the new modified skyhook strategy to control the full vehicle vibration problem. Nowadays, many researchers are working on active tilting technology to improve vehicle cornering. But in those work, the effect of road bank angle is not considered in the control system design or in the dynamic model of the tilting standard passenger vehicles. The non-incorporation of road bank angle creates a non-zero steady-state torque requirement. Therefore, in this manuscript, this phenomenon was addressed while designing the direct tilt control and the dynamic model of the full car model.

This book has indicated the potential of the SKDT suspension system in improving cornering performances of the vehicle and paves the way for future work on vehicle's integrated system for chassis control.

Keywords Quarter-car • Vehicle • Suspension • Semi-active • Skyhook • Adaptive • Control • Damper • Quanser

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Chapter 1
Introduction

Abstract In this chapter, background of this book has been described. Motivation and methodologies has been depicted in the later section. A brief outline of this manuscript has been included in the last section.

1.1 Background

One of the most important considerations of the present automotive industry is to provide passenger safety, through optimal ride comfort and road holding, for a large variety of vehicle manoeuvres and road conditions. The comfort and safety of the passenger travelling in a vehicle can be improved by minimizing the body vibration, roll and heave of the vehicle body through an optimal road contact for the tyres. The system in the vehicle that provides these actions is the vehicle suspension, i.e. a complex system consisting of various arms, springs and dampers that separate the vehicle body from the tyres and axles (Fig. 1.1). In general, vehicles are equipped with fully passive suspension systems due to their low cost and simple construction. The passive suspension consists of springs, dampers and anti-roll bars with fixed characteristics. The major drawback of the passive suspension design is that you cannot simultaneously maximize both vehicle ride and handle performance. To achieve better ride performance, a “soft” suspension needs to be introduced to maintain contact between the vehicle body and the tyre. The “soft” suspension easily absorbs road disturbances. That is why most of the luxury cars employ “soft” suspensions to provide a comfortable ride. The second characteristic of vehicle performance is the road handling. This refers to a vehicle’s ability to maintain contact between the vehicle’s tyre and the road during turns and other dynamic manoeuvres. This can be achieved by “stiff” suspensions as seen in sports cars. The challenge of the passive suspension system is in achieving the right compromise between the two characteristics of vehicle performance which will best suit the targeted consumer. However, by introducing the active or semi-active suspension system in the vehicle (Fig. 1.2), a more desirable compromise can be achieved between the benefits of the soft and stiff suspension system.

The active or semi-active suspension systems are incorporated with the active components, such as actuators and semi-active dampers, coupled with various

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Fig. 1.1 Rear suspension system without wheel of a vehicle

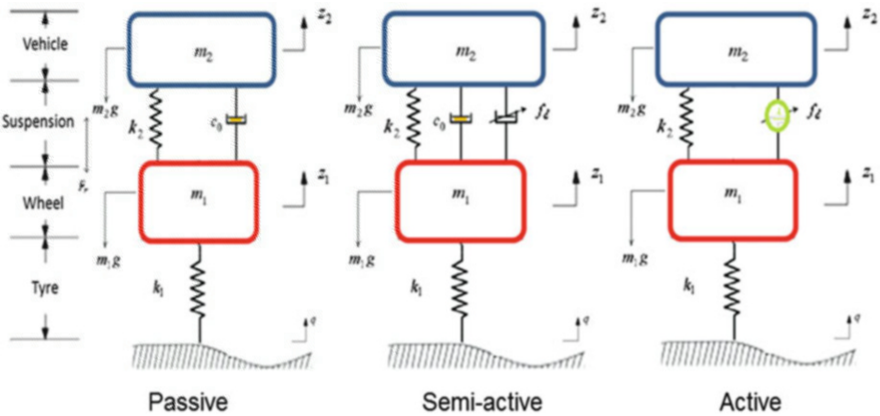

Fig. 1.2 The passive, semi-active and active suspension system

dynamic control strategies. With active components, these systems can provide adjustable spring stiffness and damping coefficients adapted to various road conditions.

Since the early 1970s, many types of active and semi-active suspension systems have been proposed to achieve better control of damping characteristics. Although the active suspension system shows better performance in a wide frequency range, its implementation complexity and cost prevent wider commercial applications. That is why the semi-active suspension system has been widely studied to achieve high levels of performance in terms of vehicle suspension system. To control the damper of the semi-active suspension system, many control strategies including skyhook surface sliding mode control [1], neural network control [2], H-infinity control [3], skyhook control, ground hook control, hybrid control [4, 5], fuzzy logic control [6, 7], neural network-based fuzzy control [8], neuro-fuzzy control [9], discrete time fuzzy sliding mode control [10], optimal fuzzy control [11], and adaptive fuzzy logic control [12, 13] have been explored. Between all of the above control systems, the skyhook control proposed by Karnopp et al. in 1974 [14] is widely used since it yields the best compromise between vehicle performance and practical implementation of semi-active suspension systems.

In the past few decades, researchers have modified the basic skyhook control strategy by adding some variations and have named them optimal, modified or adaptive type skyhook control strategies [15, 16]. But in most of these studies, skyhook gain (SG) of the control strategy remains as a constant value, and it is usually chosen from a set of values as suited for the vehicle in the simulation environment. One of the major goals of this manuscript is to present a new modified skyhook control strategy with adaptive SG.

This control strategy has also been employed on the full car model to improve the isolation of the vibration and handling the performance of the road vehicle. The full car model designed in this manuscript has nine degrees of freedom, and those are the heave modes of four wheels and the heave, lateral, roll, pitch and yaw modes of the vehicle body.

Nowadays, some researchers have focused on active steering control to improve vehicle cornering [17–19]. Three types of active steering control strategies have been proposed. These are the four-wheel active steering system (4WAS), the front wheel active steering system (FWAS) and the active rear wheel steering system (RWAS). The four-wheel active steering system (4WAS) is the combination of the rear active steering system and the front active steering system. In the FWAS system, the front wheel steer angle is determined by the steering angle generated due to the driver's direct steering input and a resultant corrective steering angle input that is produced by the design of the active front wheel steering controller.

Vehicle performance during cornering has been improved by most of the car manufacturers by using electronic stability control (ESC). Car manufacturers use different brand names for ESC, such as Volvo named it DSTC (Dynamic Stability and Traction Control); Mercedes and Holden called it ESP (Electronic Stability Program); and DSC (Dynamic Stability Control) is the term used by BMW and Jaguar, but despite the term used, the processes are almost the same. To avoid oversteering and understeering during cornering, ESC extends the brake and different torque on each wheel of the vehicle. But ESC reduces the longevity of the tyre as the tyre skids while random braking. To overcome this problem, a vehicle can be tilted inward via an active or semi-active suspension system.

The concept of "active tilting technology" has become quite popular in narrow tilting road vehicles and modern railway vehicles. Now in Europe, most new high-speed trains are fitted with active tilt control systems, and these trains are used as regional express trains [20, 21]. To tilt the train inward during cornering, tilting actuators are used as an element of the secondary active suspension system. These actuators are named as bolsters. In a road vehicle, actuators are also used to affect the vehicle roll angle via an active suspension system. Since the beginning of the 1950s, there has been extensive work done in developing the narrow tilting vehicle by both the automotive industry [22–25] and academic researchers [26–30].

This particular small and narrow geometric property of the vehicle poses stability problems when the vehicle needs to corner or change a lane. There are also two types of control schemes that have been used to stabilize the narrow tilting vehicle. These control schemes are defined as direct tilt control (DTC) and steering tilt control (STC) systems as detailed in [27, 31, 32]. A typical passenger vehicle body can be tilted up to ten degrees as the maximum suspension travel is around 0.25 m. Then, the lateral acceleration of the tilted vehicle caused by gravity can reach a maximum of about 0.17 g [33]. Since the lateral acceleration produced by normal steering manoeuvres is around 0.3–0.5 g, the active or semi-active suspension systems have the potential of improving vehicle ride handling performance [33]. Semi-active or active suspension systems can act promptly to tilt the vehicle with the help of semi-active dampers or actuators. However, the active suspension systems need to avoid over-sensitive reaction to driver's steering commands for vehicle safety. Recently Bose Corporation presented the Bose suspension system [34] in which the high-bandwidth linear electromagnetic dampers improved vehicle cornering. It is able to counter the body roll of the vehicle by stiffening the suspension while cornering. Car giant Nissan has developed a four-wheeled ground vehicle named Land Glider [35]. The vehicle body can lean into a corner up to 17° for sharper handling considering the speed, steering angle and yaw rate of the vehicle. In addition, in the works stated above and other research, the effect of road bank angle is neither considered in the control system design nor in the dynamic model of the tilting standard passenger vehicles [26, 27, 31, 32, 36–44]. Not incorporating the road bank angle creates a non-zero steady-state torque requirement. So this phenomenon needs to be addressed while designing the tilt control and the dynamic model of the full car model. To lean a vehicle which incorporates the road bank angle, the response time of the actuator or semi-active damper plays an important role.

The majority of the semi-active suspension systems use pneumatic or hydraulic solutions as the actuator or semi-active damper [45–49]. These systems are characterized by high force and power densities but suffer from low efficiencies and response bandwidths. Commercial systems incorporating electromagnetic elements (combine rotary actuators and mechanical elements) illustrate the properties of the magneto-rheological fluids in damper technology to provide adjustable spring stiffness. However, linear electromagnetic actuators appear as a better solution for a semi-active suspension system in respect of their high force densities, form factor, and response bandwidth. The motivation and the methodology of this manuscript are described in the next section.