Chapter 1

Introduction

The purpose of this chapter is to provide an introduction to the motivation for the research conducted for this thesis. First, the problems that Lord Corporation were experiencing in the development of their magnetorheological (MR) seat suspension will be discussed. This will be followed by the results of a literature search and the presentations of the objectives of the research. Finally, the organization of the manuscript is outlined.

1.1 Magnetorheological Seat Suspension Development Problems

Passive seat suspensions have long demonstrated that they are suboptimal single degree of freedom (SDOF) suspension systems. Once the spring rate has been chosen, thus setting the natural frequency, the other parameter that needs to be chosen is the system damping. Insufficient damping provides poor resonance control, but good isolation at high frequencies. Conversely, large damping results in good resonance control while sacrificing high frequency isolation. Skyhook control has been shown to be an optimal control technique for a suspension system, nearly eliminating the compromise between resonance control and high frequency isolation associated with the passive suspensions [1]. The main drawback to skyhook control is that some form of force generator must be added to the system. One approach is to add a fully active force generator. This is often accomplished with a hydraulic actuator and power supply. It has been shown over the years that active suspensions require a considerable amount of energy to operate and can be quite complex. Semiactive force generators, or semiactive dampers, on the other hand, develop their force in a passive manner by changing the damping level in a wide range.

Lord Corporation has been working on semiactive suspensions for the past two decades. They have recently begun to apply the technology of MR fluids to semiactive dampers. One potential application of MR semiactive dampers is the seat suspension commonly found on heavy vehicles. This market has been fueled by the ever-tightening standards aimed at protecting the health and well-being of the vehicle operators.

Lord has developed several control policies for controlling the damper in MR seat suspensions. They found, however, that the skyhook control policy achieved what they desired: high frequency isolation along with resonance control. Although the skyhook control performed well in terms of standardized tests required for certification, the subjective performance was poor. Passengers in the seat often described the feel as "jerky" or "nervous." Lord engineers also noticed that when comparing output acceleration frequency spectra to input spectra, the seat seemed to be responding at frequencies that did not exist in the input. The poor subjective feel was immediately attributed to the unexpected response since it occurred in the 4-8 Hz frequency range, in which the human body is most sensitive.

1.2 Literature Review

An extensive literature search was conducted to determine the past studies in the area of semiactive and magnetorheological seat suspensions. Figure 1.1 shows a flow chart of the literature search according to the keywords and the number of "hits" for each keyword. The database INSPEC, which is one of the major databases in engineering, was used for this search. Although the database may not be all-inclusive, it includes the vast majority of the open literature studies.

This literature search resulted in a large number of articles in general areas such as "seat," "suspensions," vehicles," and "hybrid." The main keywords, such as "semiactive," "magnetorheological," "skyhook," and "groundhook," yielded a manageable number of hits, and were inspected to find the relevant articles. The larger number of hits were quickly narrowed by refining the search until a manageable number of articles were found. The keyword search for "vehicle suspensions" yielded a great number of hits, but it did not need to be narrowed any further since all of the other keywords hits had been searched. For example, narrowing "vehicle suspension" with "magnetorheological" would only result in the union of the two sets. However, "magnetorheological" had already been inspected, so all articles in the union had also been inspected.

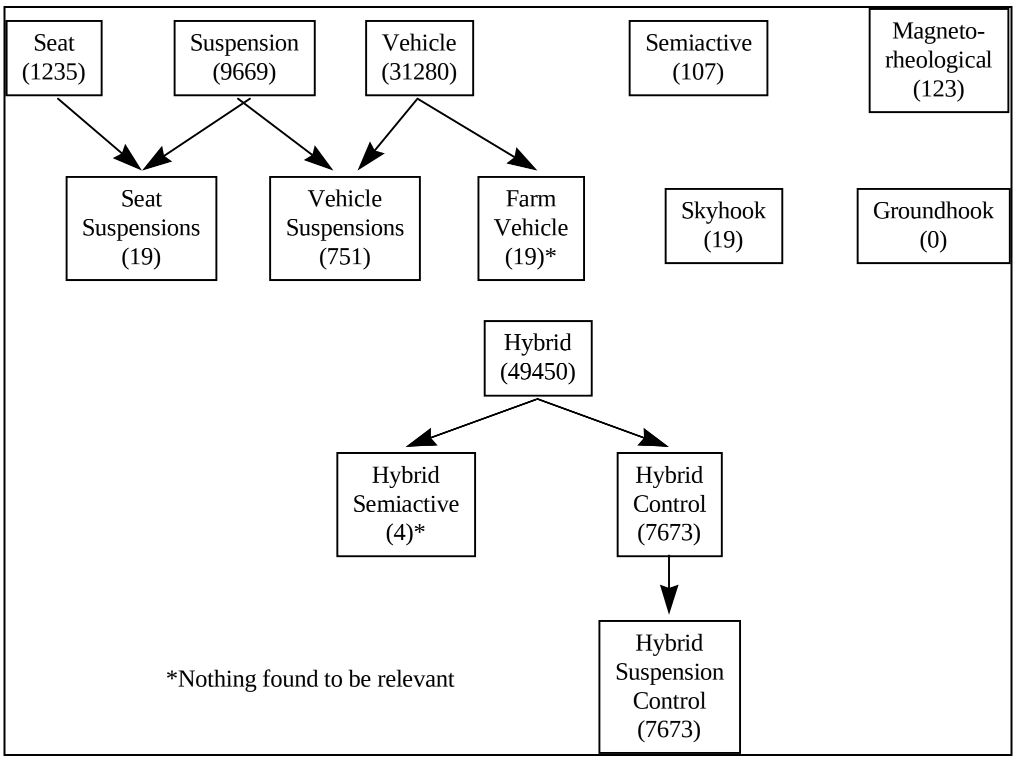

Figure 1.1. Literature Search Flow Chart According to Keywords and Number of "Hits."

1.2.1 Keyword: Semiactive

The majority of the studies in the area of semiactive suspensions used a two-degree-of-freedom (2DOF) model representing single suspensions [1-10]. There were a few studies in the area of single-degree-of-freedom (SODF) systems [11-13]. Lieh [14] explores the use of semiactive suspensions to control the dynamics of a full car model. He concludes that the use of the skyhook control policy reduces the root mean square (RMS) acceleration of the car body while increasing the RMS tire forces.

Two studies, one by Yi and Hedrick and the other by Valesek *et al*., were found to be in the area of dynamic tire loading [1, 2]. Both studies were interested in methods to reduce the dynamic tire loading of a vehicle in order to reduce the amount of road damage that it causes.

Three other studies focused on control methods that are able to teach themselves how to control the semiactive suspension system. Cheok and Huang [11] and Yoshimura *et al*. [3] used fuzzy logic and neural network methods to teach the controller, while Frost *et al*. [4] use a moderated reinforcement learning technique. All three studies show that there are benefits associated with these types of control approaches.

The next study by Margolis [12] examines the effects of using realistic feedback signals when controlling active and semiactive suspension systems. This is an analytical study that suggests several feedback strategies for the semiactive suspension system so that the performance can approach the fully active suspension performance. In another study by Margolis [5], he outlines a procedure to examine the feasibility of using semiactive or active vibration isolation instead of purely passive approaches.

Hwang *et al.* [6] present an interesting method for testing the semiactive damper hardware without using a complete vehicle. They explore the test method known as a hardware in the loop simulation. Essentially, the dynamic model of the system is coded for simulation in a computer. The piece of hardware under test (i.e., the semiactive damper) is excited according to the computer numerical simulation, and the response of the hardware is measured and fed back into the computer to complete the simulation.

The other five studies we reviewed deal with the optimal and robust control or the tuning of semiactive suspension systems. Jezequel and Roberti [7] investigated optimal preview of the suspension system which is useful for trains: once the lead train passes over a point, the rest of the train has knowledge of the track conditions. Miller [8] explored the effects of the levels of both on-state and off-state damping on the performance of the quarter car semiactive suspension system. Bellizzi and Bouc [13] and Hrovat, *et al*. [9] studied optimal control techniques for the semiactive suspension, while Tibaldi and Zattoni [10] studied the robustness of linear quadratic Gaussian control techniques.

1.2.2 Keyword: Magnetorheological

The first three studies in the area of magnetorheological fluids deal with characterizing the properties of MR fluids. Lazareva and Shitik [15] studied the properties of MR fluids that are based on barium and strontium ferrites and iron oxides. The fluids were prepared using various combinations of the materials, and their properties, such as the MR effect, were studied. Ashour *et al.* [16] studied the effects of components of the MR on sedimentation of the magnetic particles and initial viscosity. An attempt was made to optimize the composition of the fluid such that the fluid had the desired properties. In another study, Ashour *et al.* [17] studied the general composition of MR fluid along with the methods that are used to evaluate the performance of the fluids. There is also an introduction to the fundamental MR devices to exploit the MR effect.

The next three studies explore the design of MR fluid devices. Carlson *et al.* [18] studied the advantages of MR over ER fluid devices in areas such as the yield strength, the required working volume of fluid, and the required power. The operational modes of the MR fluid are presented along with the linear fluid damper, the rotary brake, and the vibration damper. Kordonsky [19] developed the concept of the MR converter (or valve) and applies the MR converter to create devices such as the MR linear damper, the MR actuator, and the MR seal. Finally Bolter and Janocha [20] examined the rules that should be applied when designing the magnetic circuit for MR devices that are working in the different modes of the MR fluid. Bolter also examined the use of permanent magnets in the design of the magnetic circuit to change the operational point of the MR device.

The final magnetorheological article by Jolly *et al.* [21] presents a model based on dipolar interaction of particles, and is used to predict the behavior of both MR fluids and MR elastomers. The model is compared to experimental data and it is shown that the model is semi-empirical in that it must be fit to the experimental data by adjusting a parameter that accounts for unmodelled magnetic interactions.

1.2.3 Keyword: Seat Suspensions

The INSPEC search for the keyword "seat suspensions" yielded only nineteen articles. Of the nineteen articles, only four were relevant to this study. In the first article, Ballo [22] analytically derives the required power usage for active seat suspension systems. The first system is actually a combination of a hydraulic actuator and passive suspension in series, while the second system is an active electro-pneumatic system which controls vibrations by controlling the air flow in and out of a pneumatic spring. For both systems, Ballo also experimentally measures the power consumption and finds that in either case, active systems require a considerable amount of power.

The next two studies were aimed at designing controllable seat suspensions from scratch. Grimm *et al.* [23] designed a fully active seat suspension for farm vehicles using a hydraulic actuator. They used a simple compensator to control the actuator using the relative displacement of the seat and either of the base or seat acceleration. Even though the compensator is very basic, their results show an improvement over passive suspensions. Nevala *et al.* [24] take the design of the seat suspension even further. They designed and mathematically modeled a 2DOF seat suspension that not only allows for vertical translation of the seat, but also allows the seat to rotate fore and aft. Even though the seat is completely modeled, there is no mention of a control strategy for the novel suspension.

The final seat suspension study is by Wu and Griffin [25] and focuses on reducing endstop impacts on a seat suspension. They accomplish this by using a two-state damper. When the seat is at the midstroke band of the suspension, the damper is turned off. As the damper moves into a band near the endstop, the damper is turned on. They have experimented with changing the size of the bands and observing the effects on the number of endstop hits.

1.2.4 Keyword: Skyhook

Of the nineteen articles hit using the keyword "skyhook," only four were found to be of relevance. Karnopp [26] contributes an excellent review of many of the past efforts in the area of semiactive suspension design. He also presents a very good background of the information that is required to understand semiactive suspension systems. Finally, he discusses several semiactive suspension applications.

Cebon *et al.* [27] discuss the different control strategies that are available for 2DOF semiactive systems. They apply modified skyhook damping and linear optimal control with full state feedback along with simple on-off control strategies in order to reduce both the tire force and body acceleration of a heavy truck. They compare the results of their mathematical simulations to their experimental testing using a hardware-in-the-loop test method. They conclude that, compared to passive suspensions, the full state feedback methods works the best in reducing tire loads and body acceleration according to simulation and experimental results.

Hrovat and Hubbard [28] study the SDOF suspension system and the application of linear quadratic regulator control theory to optimize the suspension in terms of rattlespace, acceleration, and jerk. Their system includes both the well-known skyhook damper and a skyhook spring.

Finally, the skyhook study by Satoh *et al*. [29] is a practical realization of a fully active skyhook suspension system on a passenger vehicle. The controller responds to the pitch and roll motions of the vehicle, as well as the vertical motion of the wheels. The results in an actual vehicle showed marked improvements over the passive suspension.

1.2.5 Keyword: Hybrid Suspension Control

The only article of interest found for this keyword was a study by Suda and Shiiba [30], which attempts to reduce the power consumption of a fully active suspension system by including a regenerative system to the suspension system. A power source is able to supply power to the suspension system when it is required to add energy to the system. Conversely, when the suspension is required to dissipate energy, energy is produced using DC generators and is stored to be used to power the active system. Through numerical simulations and basic experiments, it was found that the hybrid suspension system had higher vibration reduction and lower power requirements.

1.3 Research Objective

The primary purpose of this study is to improve the application of magnetorheological dampers for seat suspensions. Specifically, this study explores the source of ride roughness due to MR dampers and introduces solutions for eliminating it.

1.4 Outline

Chapter 2 presents the background information necessary to understand semiactive suspension systems and skyhook control. Chapter 2 also discusses the construction and performance of magnetorheological dampers. Chapter 3 describes the Isringhausen seat suspension and the design of the Lord MR seat suspension controller. The entire controller will be discussed, including the hardware and software components. Chapter 4 presents the experimental setup that was used for this study. It includes the seat test structure as well as the sensors and data acquisition equipment. Chapter 5 includes the experimental and analytical frequency analysis of the seat suspension, and the source of the unexpected peak in the seat acceleration spectrum. In addition, several methods to remove the peak are developed and tested. Chapter 6 investigates the time domain data for the suspension to determine the source of the poor subjective feel. It also suggests solutions for correcting the problem and evaluates their effectiveness. Next, Chapter 7 discusses the results of a preliminary testing of groundhook and hybrid control policies. The policies are introduced since the system ceases to be a simple single-degree-of-freedom system when the entire vehicle is considered. Finally, Chapter 8 summarizes all of the results from this study and provides recommendations for future work.