Chapter 2

Background

This chapter includes an overview of some of the concepts that are essential to this research. The first part of the chapter includes a review of magneto-rheological dampers, passive and semiactive suspension systems, and adaptive control concepts. The second part of the chapter includes the results of a literature review that was conducted for this study. This literature review provides a summary of some of the studies that were found on the subjects related to this research.

2.1 Magneto-Rheological Dampers

The purpose of this section is to introduce the theoretical and practical applications of a magnetorheological (MR) fluid for a controllable MR damper. First, the concept of the MR fluid will be introduced. Next, the practical realization of MR dampers will be discussed. Finally, the performance of the MR damper used for this research will be investigated.

2.1.1 Magneto-Rheological Fluids

Magneto-rheological fluids are materials that exhibit a change in rheological properties (elasticity, plasticity, or viscosity) with the application of a magnetic field. The MR effects are often greatest when the applied magnetic field is normal to the flow of the MR fluid. Another class of fluids that exhibit a rheological change is electrorheological (ER) fluids. As the name suggests, ER fluids exhibit rheological changes when an electric field is applied to the fluid. There are, however, many drawbacks to ER fluids, including relatively small rheological changes and extreme property changes with temperature. Although power requirements are approximately the same [5, 6], MR fluids only require small voltages and currents, while ER fluids require very large voltages and very small currents. For these reasons, MR fluids have recently become a widely studied 'smart' fluid.

Besides the rheological changes that MR fluids experience while under the influence of a magnetic field, there are often other effects such as thermal, electrical, and acoustic property changes. In the area of vibration control, however, the MR effect is most interesting since it is possible to apply the effect to a hydraulic damper. The MR fluid essentially allows one to control the damping force of the damper by replacing mechanical valves commonly used in adjustable dampers. This offers the potential for a superior damper with little concern about reliability, since if the MR damper ceases to be controllable, it simply reverts to a passive damper.

2.1.2 Construction of an MR Damper

Magnetorheological (MR) fluids are manufactured by suspending ferromagnetic particles in a carrier fluid. The ferromagnetic particles are often carbonyl particles, since they are relatively inexpensive. Other particles, such as iron-cobalt or iron-nickel alloys, have been used to achieve higher yield stresses from the fluid [6]. Fluids containing these alloys are impractical for most applications due to the high cost of the cobalt or nickel alloys.

A wide range of carrier fluids such as silicone oil, kerosene, and synthetic oil can be used for MR fluids. The carrier fluid must be chosen carefully to accommodate the high temperatures to which the fluid can be subjected. The carrier fluid must be compatible with the specific application without suffering irreversible and unwanted property changes. The MR fluid must also contain additives to prevent the sedimentation of and promote the dispersion of the ferromagnetic particles.

A top-level functional representation of the MR damper is shown in Fig. 2.1. The fluid that is transferred from above the piston to below (and vice-versa) must pass through the MR valve. The MR valve is a fixed-size orifice with the ability to apply a magnetic field, using an electromagnet, to the orifice volume. This results in an apparent change in viscosity of the MR fluid, causing a pressure differential for the flow of fluid which is directly proportional to the force required for moving the damper rod.

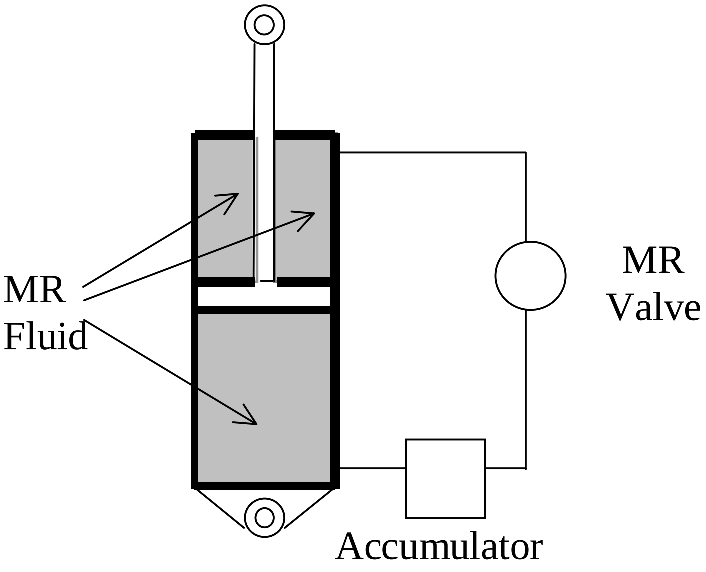
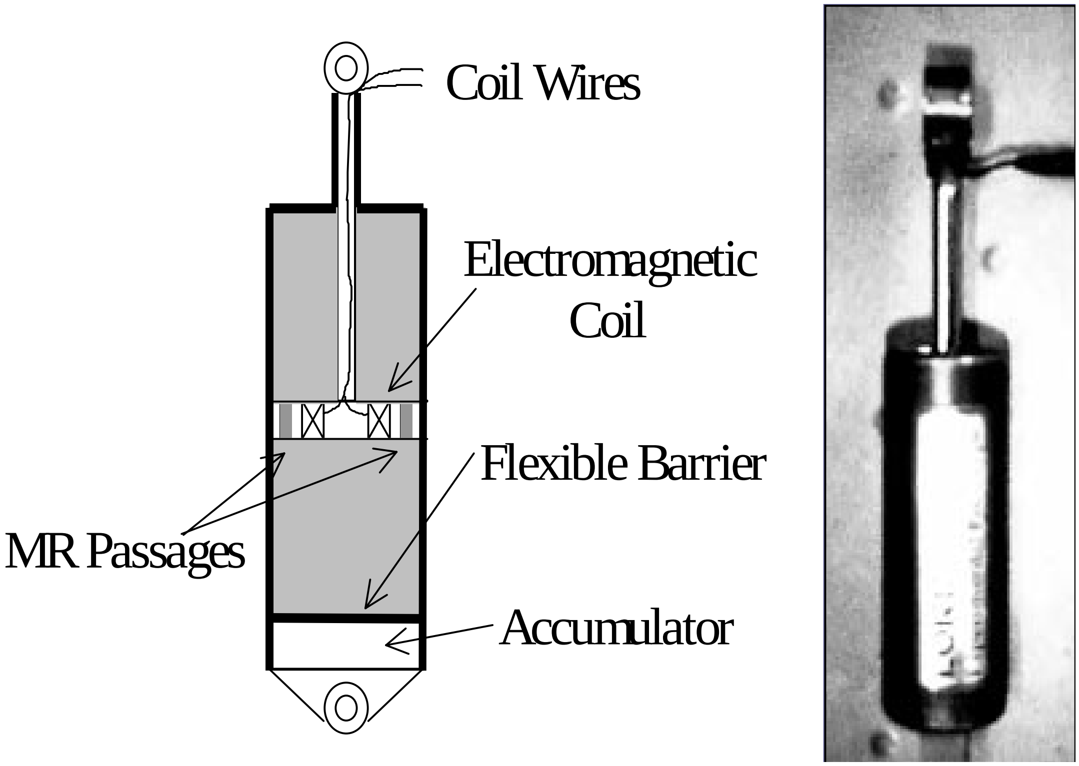


Figure 2.1 Functional Representation of an MR Damper

The accumulator is a pressurized volume of gas that is physically separated from the MR fluid by a floating piston or bladder. The accumulator serves two purposes. The first is to provide a volume for the MR fluid to occupy when the shaft is inserted into the damper cylinder. The second is to provide a pressure offset so that the low-pressure side of the MR valve is not reduced enough to cause cavitation of the MR fluid.

An elegant and compact design of the MR damper developed by Lord Corporation and used for this research is shown in Fig. 2.2. All of the external components have been incorporated internally. This provides a compact design that is very similar in size and shape to existing passive dampers. The only external parts are the two electrical leads for the electromagnet, which are connected to the controller.



(a) (b)

Figure 2.2 Lord MR Seat Damper: (a) Schematic Representation, (b) Actual Hardware

2.1.3 Performance of the MR Damper

For typical passive dampers, the damper performance is often constitutively characterized by using the force vs. velocity relationship. For an ideal viscous damper, the force vs. velocity performance is shown in Fig. 2.3. The slope of the force vs. velocity line is known as the damper coefficient, C. Frequently, the force vs. velocity line is bilinear and asymmetric, with a different value of C for jounce (compression) and rebound (extension), as shown in Fig. 2.4. In the case of a vehicle suspension, the damping curve is shaped (or tuned) by a ride engineer for each particular application. Therefore, the operational envelope of a passive damper is confined to a pre-designed force-velocity characteristic.

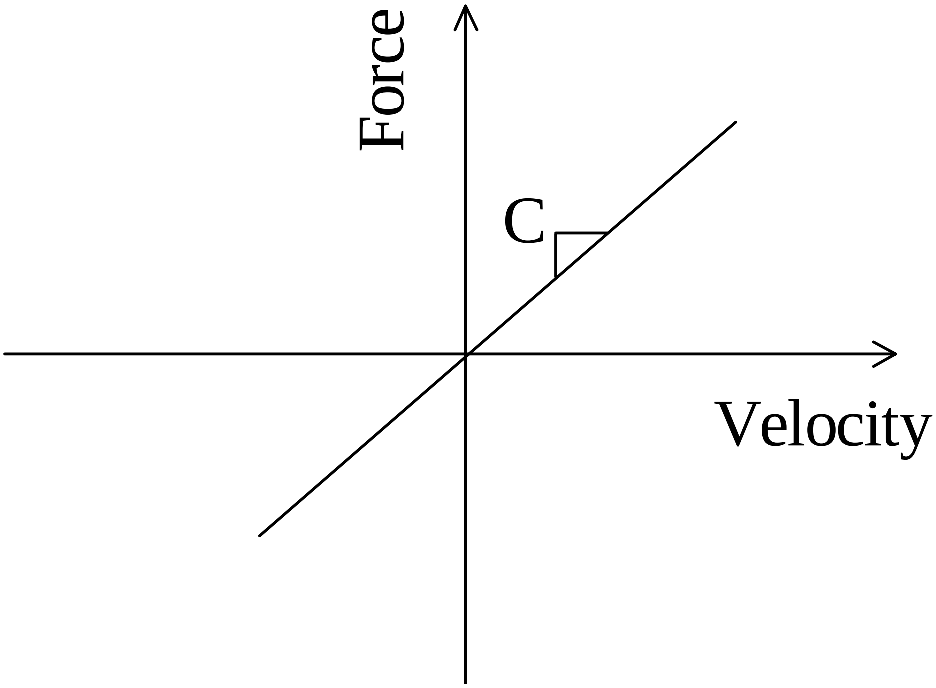


Figure 2.3 Linear Damper Characteristics

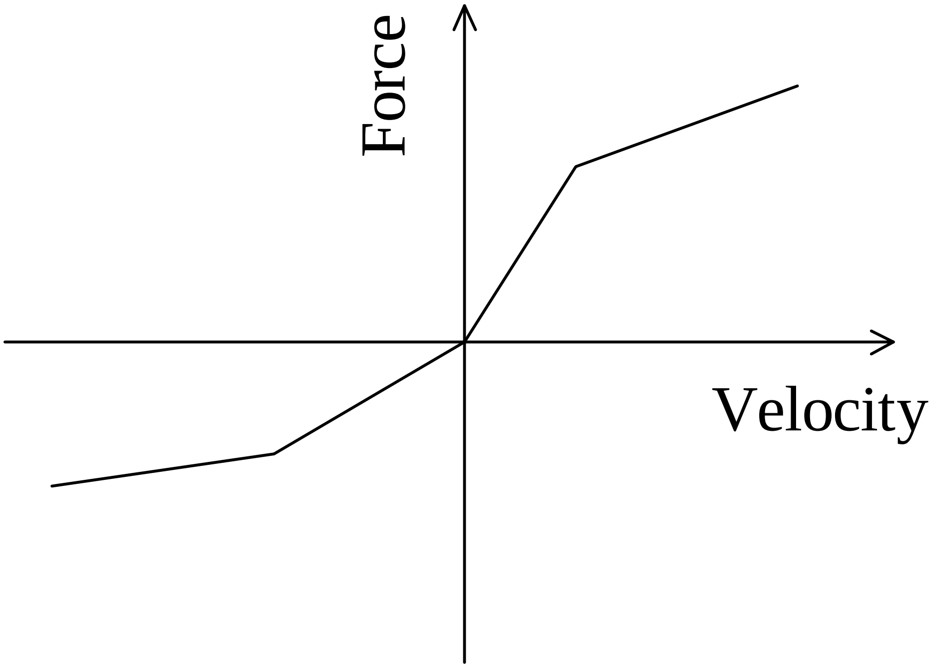


Figure 2.4 Bilinear and Asymmetric Damping Characteristics

In the case of MR dampers, the ideal force vs. velocity characteristics are as shown in Fig. 2.5. This results in a force vs. velocity envelope that can be described as an area rather than a line in the force-velocity plane. Effectively, the controller can be programmed to emulate any damper force-velocity characteristic or control policy within the envelope.

We can model the ideal MR damper according to

$$F_{MRDAMPER} = -\alpha\, sign(v_{rel}) \tag{2.1}$$

where α is a constant, i is the damper current, and v_{rel} is the velocity across the damper.

Figure 2.6 shows the nonlinear force-velocity characteristics for the MR damper used for this research. The model in Eq. (2.1) and Fig. 2.5 does not capture the fine details of the actual MR damper, but it captures the gross behavior of the MR damper.

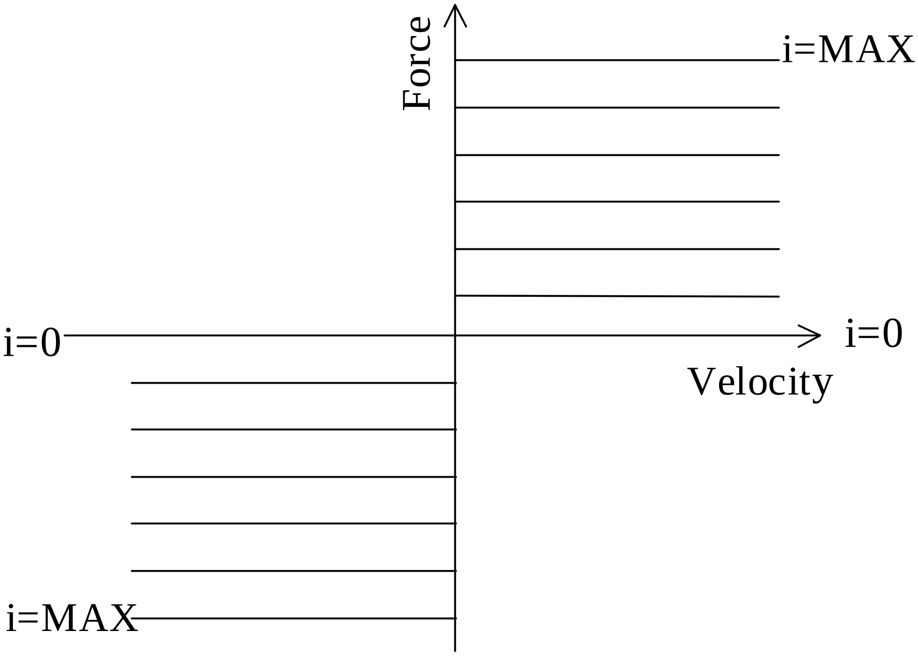


Figure 2.5 Ideal MR Damper Performance

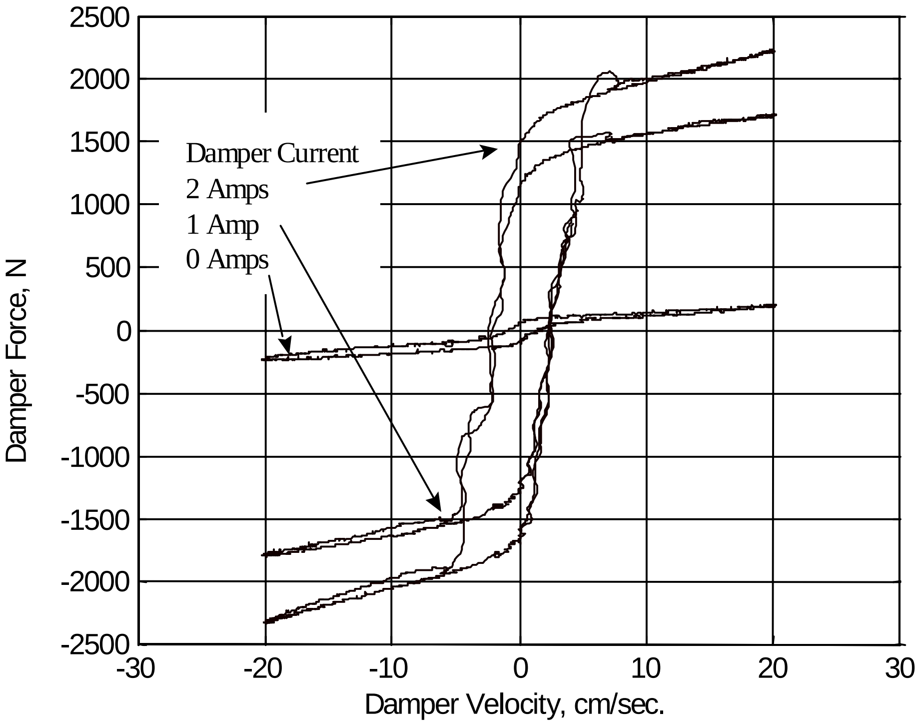


Figure 2.6 MR Damper Performance Envelope from Experimental Data

Some of the effects missing from the model include the magnetic field saturation, hysteresis, and the force due to the pressurized accumulator. As will be discussed in Chapter 3, more sophisticated models are needed to capture such effects of MR dampers.

2.2 Passive and Semiactive Vibration Control

This section will introduce the concepts of passive and semiactive control for base excited systems such as the one shown in Fig. 2.7. A passive suspension system is one in which the characteristics of the components (springs and dampers) are fixed. The characteristics are determined by the designer, according to the design goals and intended application of the suspension. Semiactive suspensions, which date back to the early 1970’s, retain the spring element and use a minimal amount of energy to change the damping force of an adjustable damper. The damping force is changed according to a control policy that is designed for the specific application and needs of the suspension system. Among the many control policies that have been proposed for the semiactive systems in the past three decades, skyhook control — first proposed by Karnop and Crosby in 1972 [1, 16, 17] — has been most widely studied. We will discuss the skyhook control policy later in this section.

For passive dampers, the transmissibility ratio between the output displacement y_1 and the input displacement y_2 can be derived as

$$\frac{y_1}{y_2} = \frac{1 + j2\zeta_P(\frac{\omega}{\omega_n})}{1 - (\frac{\omega}{\omega_n})^2 + j2\zeta_P(\frac{\omega}{\omega_n})} \tag{2.2}$$

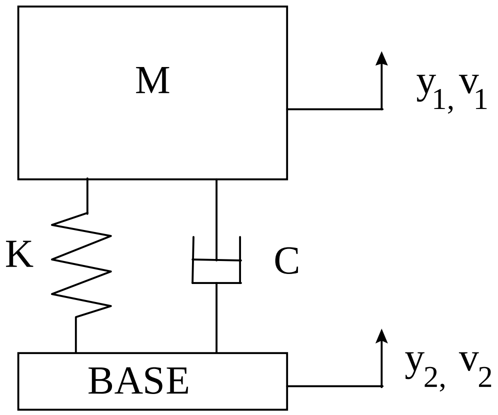


Figure 2.7 SDOF Passive Base-Excited System

where ζ_P is the passive damping ratio [18]. We can then plot the transmissibility as a function of the quantity ω/ω_n, resulting in Fig. 2.8 for various damping ratios. Notice that at low passive damping ratios, the resonant transmissibility (around $\omega = \omega_n$) is relatively large, while the transmissibility at frequencies above the resonant peak is quite low. The opposite is true for relatively high damping ratios. Figure 2.8 demonstrates the inherent tradeoff of passive seat suspension systems. If we choose a low damping ratio, we gain superior high frequency isolation but poor resonant frequency control. However, as we increase the damping ratio, we begin to trade off the high frequency isolation for resonance control. The semiactive control policies tend to control the suspension such that a mere favorable compromise between the resonant control and high frequency harshness is achieved [19].

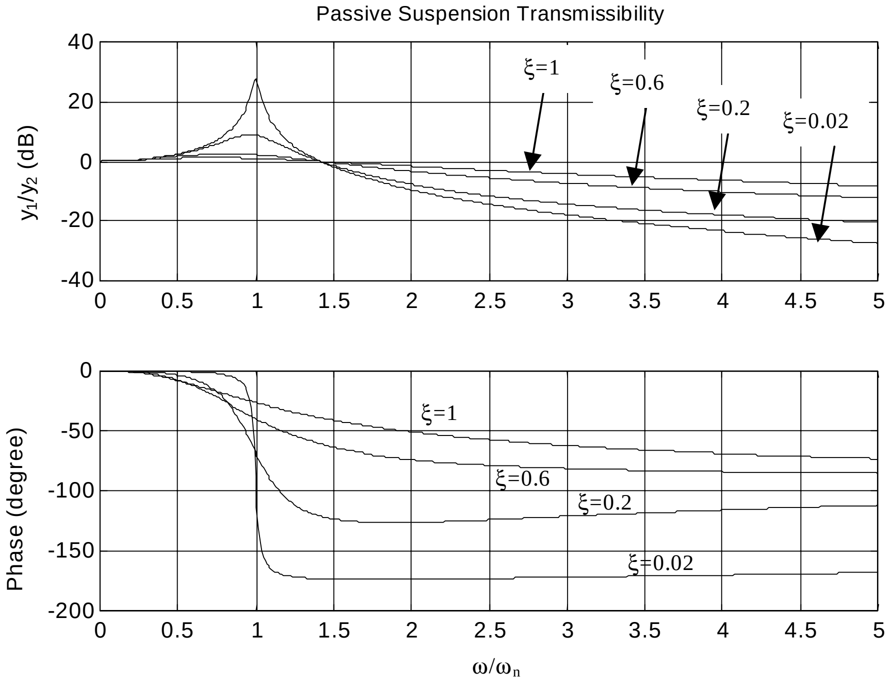


Figure 2.8 Passive Suspension Transmissibility

2.2.1 Ideal Skyhook Control

One method to eliminate the tradeoff between resonance control and high frequency isolation is to reconsider the configuration of the suspension system. For instance, consider moving the damper from between the suspended mass and the base to the position shown in Fig. 2.9. The damper is now connected to an inertial reference in the sky (i.e., a ceiling that remains vertically fixed relative to a ground reference). Notice that this is a purely fictional configuration, since for this to actually happen, the damper must be attached to a reference in the sky that remains fixed in the vertical direction, but is able to translate in the horizontal direction. Ignoring this problem at the moment, we will focus on the performance of this configuration.

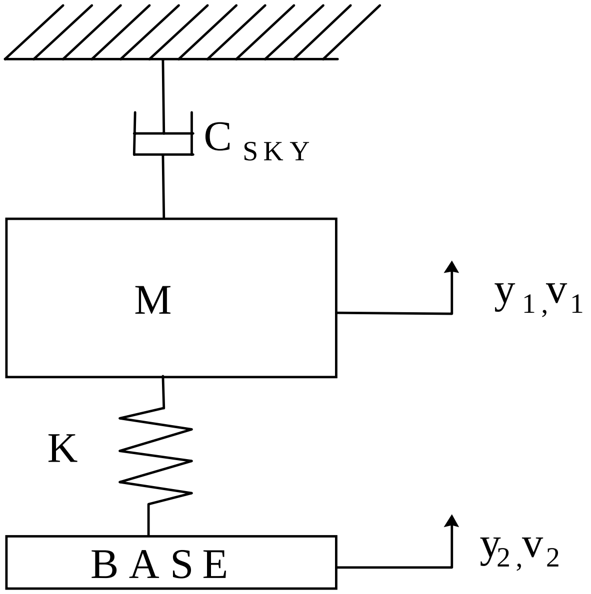


Figure 2.9 Ideal Skyhook Configuration

The transmissibility of this configuration can be derived to be

$$\frac{y_1}{y_2} = \frac{1}{1-(\frac{\omega}{\omega_n})^2 + j2\zeta_P(\frac{\omega}{\omega_n})} \tag{2.3}$$

where, in this case, ζ_{SKY} is the skyhook damping ratio. Once again, if we plot the transmissibility for various values of ζ_{SKY}, we find the results shown in Fig. 2.10. As in the passive case, as the skyhook damping ratio increases, the resonant transmissibility decreases. Increasing the skyhook damping ratio, however, does not increase the transmissibility above the resonant frequency. For sufficiently large skyhook damping ratios (i.e., above $\zeta>0.707$), we can isolate even at the resonance frequency. This is encouraging since we have removed the tradeoff associated with passive dampers.

There exist a large number of studies on the effectiveness of the skyhook control policy along with other optimal control techniques. Most of these studies indicate that skyhook control is the optimal control policy in terms of its ability to isolate the suspended mass from the base excitations [2-4].

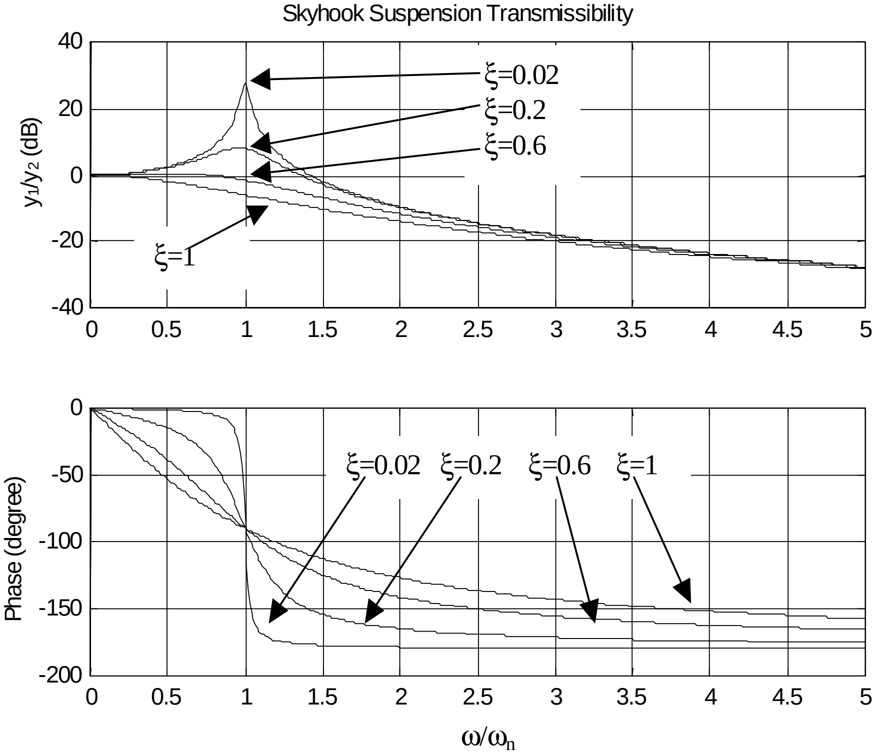


Figure 2.10 Ideal Skyhook Transmissibility

One method of generating the skyhook damping force is to remove the passive suspension (i.e., both the damper and the spring) and replace it with an active force generator. This can be achieved by using a hydraulic actuator, however, the resulting system is rather complex and requires a significant amount of power [4]. Another approach to achieving skyhook damping is to use semiactive dampers. Semiactive dampers allow for the damping coefficient, and therefore the damping force, to be varied between high and low levels of damping. Early semiactive dampers were mechanically adjustable by opening or closing a bypass valve. The only power required for the damper is the relatively small power to actuate the valve. For this research, we are using a magnetorheological damper which varies the damping by electrically changing the magnetic field applied to the magnetorheological fluid. The SDOF model shown in Fig. 2.7 modifies to Fig. 2.11, where the damping coefficient, $C_{CONTROLLABLE}$, varies over time. This configuration will be referred to as the semiactive suspension.

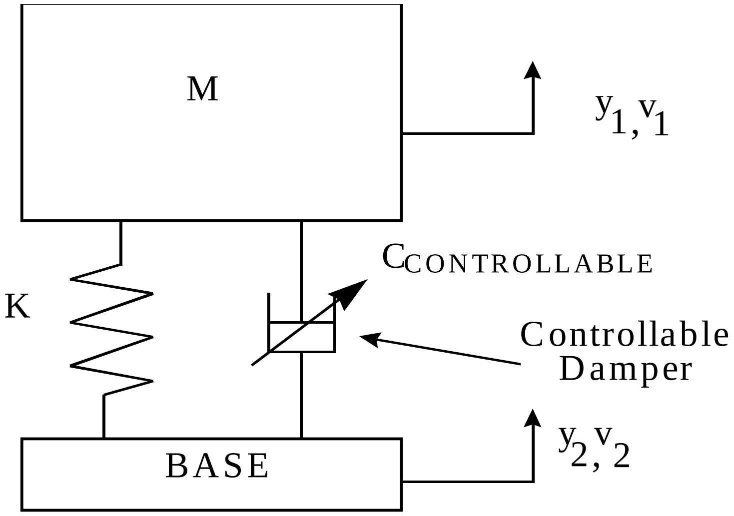


Figure 2.11 Semiactive Suspension

2.2.2 Semiactive Realization of Skyhook Control

Once we have decided to use a semiactive damper, we must determine how to modulate the damper such that it emulates a skyhook damper. We first define the velocity of the suspended mass relative to the base, v_{12}, to be positive when the base and mass are separating (i.e., $v_{12} = v_1 - v_2$) for both systems. Now assume that for both systems, the suspended mass is moving upwards with a positive velocity v_1. If we consider the force that is applied by the skyhook damper to the suspended mass, we notice that it is in the negative y_1 direction, or

$$F_{SKY} = -C_{SKY} V_1 \tag{2.4}$$

where F_{SKY} is the skyhook force. Next, we need to determine if the semiactive damper is able to provide the same force. If the base and suspended mass in Fig. 2.11 are separating, then the semiactive damper is in tension. Thus, the force applied to the suspended mass is in the negative y_1 direction, or

$$F_{CONTROLLABLE} = -C_{CONTROLLABLE} V_{12} \tag{2.5}$$

where $F_{CONTROLLABLE}$ is the force of an ideal damper applied to the suspended mass. Since we are able to generate a force in the proper direction, the only requirement to match the skyhook suspension is

$$C_{CONTROLLABLE} = C_{SKY} \frac{V_1}{V_{12}} \tag{2.6}$$

To summarize, if v_1 and v_{12} are positive, $C_{CONTROLLABLE}$ should be defined as in Eq. (2.6).

Now consider the case in which the base and suspended mass are still separating, but the suspended mass is moving downwards with a negative velocity v_1. In the skyhook configuration, the damping force will now be applied in the upward, or positive, y_1 direction. In the semiactive configuration, however, the semiactive damper is still in tension, and the damping force will still be applied in the downward, or negative, direction. Since the semiactive damping force cannot possibly be applied in the same direction as the skyhook damping force, the best that can be achieved is to minimize the damping force. Ideally, the semiactive damper is desired to be set so that there is no damping force, but in reality there is some small damping force present and it is not in the same direction as the skyhook damping force. Thus, if v_{12} is positive and v_1 is negative, we need to minimize the semiactive damping force.

We can apply the same simple analysis to the other two combinations of v_1 and v_{12}, resulting in the well-known semiactive skyhook control policy [1]:

$$\begin{cases} v_1 v_{12} > 0 & F_{SA} = C_{SKY} v_1 \\ v_1 v_{12} < 0 & F_{SA} = 0 \end{cases} \tag{2.7}$$

where F_{SA} is the semiactive skyhook damper force. Equation (2.7) implies that when the relative velocity across the suspension (v_{12}) and sprung mass (v_1) have the same sign, a damping force proportional to v_1 is desired. Otherwise, the minimal amount of damping is desired. Further Eq. (2.7) provides a very simple method to emulate the ideal skyhook suspension system using only a semiactive damper.

2.3 Adaptive Control Concepts

According to the Longman English Dictionary, “adaptive” means “to be able to be changed or change to be suitable for new needs, different conditions, etc.”. In general, the plants to be controlled possess uncertainties. Thus, even though there exist many classical and modern control design methods that are able to achieve satisfactory performance for the fixed and known plants, adaptive control design is still an active topic, as reflected in the surge of publications and development efforts from academic research and industrial applications. Adaptive controllers possess the essential ability to deal with the uncertainties or changes induced from internal systems and external environments.

Usually, an adaptive control approach can be developed from one of the following basic methods [8]

(1) Sensitivity methods: the estimated parameters in the adaptive control are adjusted in a direction that minimizes a certain performance function. The stability of this type of adaptive systems is either weak or cannot be established.

(2) Positivity and Lyapunov design: adaptive laws are developed by applying the direct method of Lyapunov and its relationship with positive real functions.

(3) Gradient method and least-square methods based on estimation error cost criteria: the estimation error is minimized with respect to the estimated parameters by using the gradient and least-squares.

Different adaptive control algorithms have been developed to cope with different dynamic systems and achieve design objectives [8-10, 20-22]. Some typical methods are model reference adaptive control, self-tuning regulators, adaptive pole placement, robust adaptive control, and least-mean-square (LMS) adaptive filters.

2.3.1 Model Reference Adaptive Control (MRAC)

As shown in Fig. 2.12, MRAC can force the plant with uncertainties to follow a specified input. The advantage of this control method over the fixed feedback controllers can be [21]

1. Do not need full state feedback or observers to access unmeasured variables
2. Applicable to non-minimum phase systems, and
3. Able to optimize the system performance and cope with system changes.

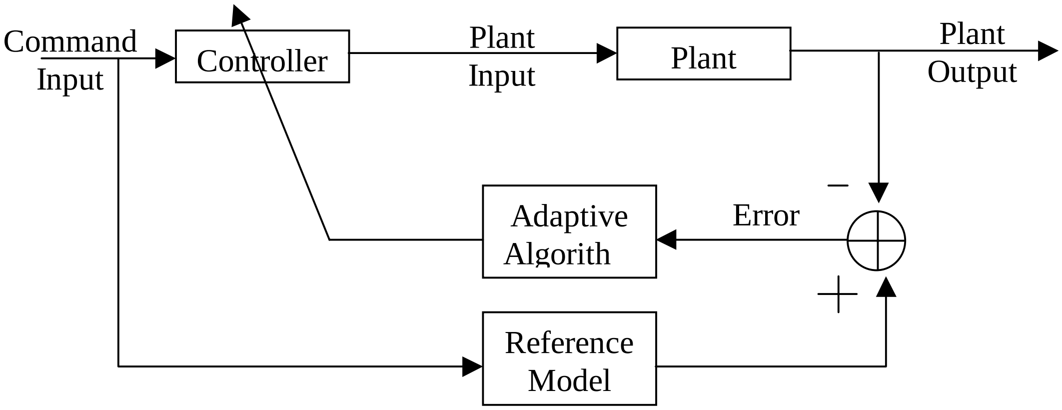


Figure 2.12 Model Reference Adaptive Control

Some of the most recent work in the input-output approach to MRAC is stability in the presence of disturbances and unmodeled dynamics, which has become known as the robust adaptive control problem, [8, 21]. Robust stability has been proposed for SISO MRAC systems. But it is only a necessary condition, and the sufficient conditions for stability need to know the relative degree of each element of the modeled part of the plant transfer matrix and require that either the left or right interacter matrix be known and diagonal. Furthermore, the choice of the reference model is restricted based upon a relationship involving an upper bound on the observability index of a quantity related to the modeled part of the plant transfer matrix [21].

2.3.2 Self-Tuning Regulator

An important result in adaptive control design is the self-tuning regulator, proposed by Astrom and Wittenmark [23]. Figure 2.13 is a generic representation of such a control approach.

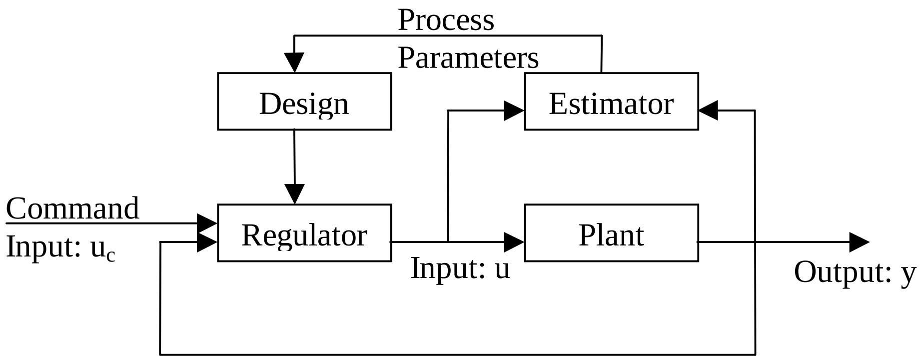


Figure 2.13 Self-Tuning Regulator

In this design, the plant responds to its own input u. Its output y includes disturbances in addition to the response induced from the plant input u. An estimator, receiving both plant input and output, estimates the plant parameters. Then these estimates are fed to an automatic design algorithm that sets the parameters of the regulator. As such, this kind of adaptive control induces recursive parameter estimation. Various formulations of self-tuning regulators have been developed by applying different recursive estimation methods, such as recursive least square (RLS), recursive extended least square (RELS), recursive instrumental variables (RIV), recursive maximum likelihood (RML), and stochastic approximation (STA). The open problems for designing self-tuning regulators are where the designed system converges and how stability can be guaranteed. The performance of such adaptive control systems heavily depends on the estimation methods. The challenge to analyze these problems is that the control process is nonlinear and time variant, especially a comprehensive analytical treatment of the transient behavior is difficult to perform.

2.3.3 LMS Adaptive Filtering Algorithms

The least-mean-square (LMS) adaptive filtering algorithm is a gradient search approach based on the steepest descent method, Widrow and Stearns [9, 22]. An LMS adaptive filter, as shown in Fig. 2.14, is to attempt to minimize some function of the error signal by modifying a finite impulse response (FIR) filter, which models the unknown system. The reference signal is required as input to the LMS adaptive filtering algorithm.

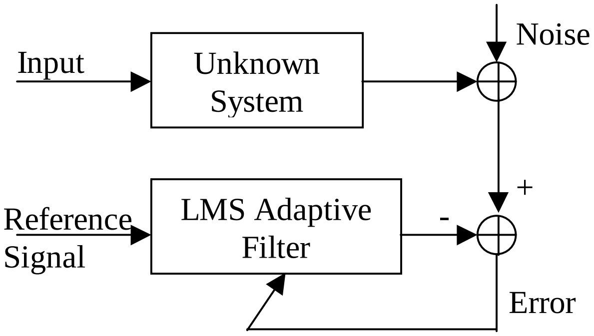


Figure 2.14 LMS Adaptive Filters

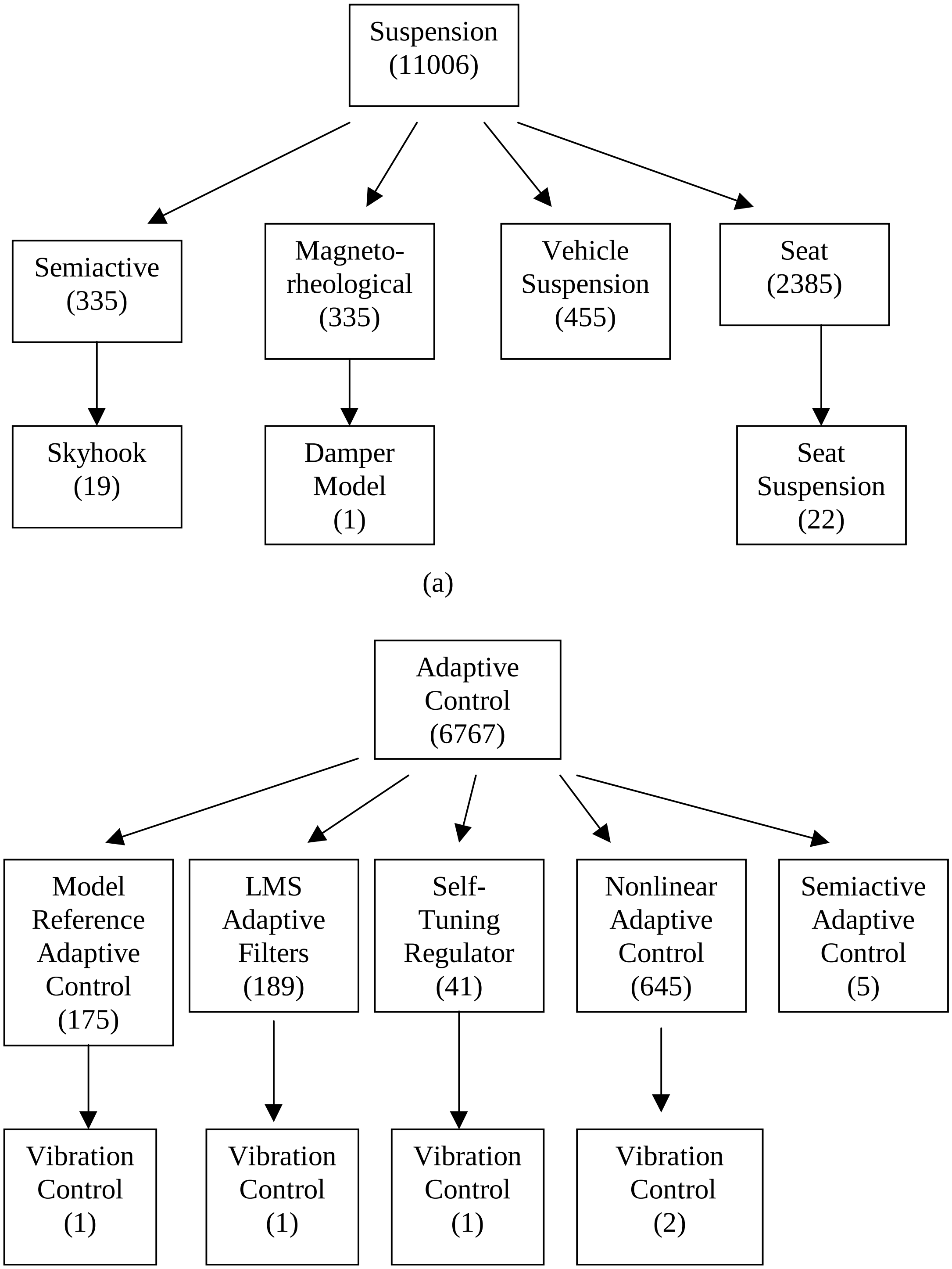
Since the adaptive filters use FIR digital filters, the error performance or cost function is a convex function of the weights. The system stability can be easily analyzed and achieved by designing a sufficient number of weights for the FIR filters and properly selecting the adaptive step size. Thus, compared to the above mentioned adaptive control approaches, the LMS adaptive filters show superior stable performance. As such, this method has been developed into different formulations, such as the filtered X-LMS adaptive algorithm, filtered U-LMS adaptive algorithm and adaptive inverse control, for linear control systems design purposes. Moreover, this control approach has been further developed for nonlinear control systems. In the next section about the literature review, we will present some typical applications of LMS adaptive filters into control systems design.

2.4 Literature Review

An extensive literature search was conducted to determine the state-of-the-art in the area of semiactive, adaptive, and vehicle suspensions. Figure 2.15 shows a flow chart of the literature search according to the keywords and the number of "hits" for each keyword. The databases Articl1st and PaperFirst, which are two of the major databases in engineering and technology, were used for this search. Articl1st includes index of articles from nearly 12,500 journals and is updated daily, while PaperFisrt is an index of papers presented at conferences with 24 times a year. As such, although the databases may not be all-inclusive, they can reflect the most recent development in the world.

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 numbers 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 “magneto-rheological” 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.

We used the key words as shown in Fig. 2.15b to search the literature relating to the adaptive control and its application to the vibration problems. Three main approaches inspected were “model reference adaptive control”, “self-tuning regulator”, and “LMS adaptive filters”. A relatively large number of publications could be found out. However, if we tried to narrow the search for vibration control, there are only a few studies to deal with vibration systems. In addition, we found out another several papers that demonstrated “semiactive adaptive control”. From the literature search, it is obvious that the adaptive vibration control is still a field for exploratory study.



(b)

Figure 2.15 Literature Search Flow Chart According to Keywords and Number of "Hits" Relating to: (a) Suspension; (b) Adaptive Control

2.4.1 Keyword: Semiactive

The majority of the studies in the area of semiactive suspensions used a two-degree-of-freedom (2DOF) model representing single suspensions [24-32]. There were a few studies in the area of single-degree-of-freedom (SDOF) systems [35, 36]. In addition, there were several studies on the combination of semiactive dampers with fuzzy logic [37-40].

Two studies, one by Yi and Hedrick [25] and the other by Valesek et al. [26], were found to be in the area of dynamic tire loading. 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.

Lieh [29] 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.

The next study by Margolis [30] 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 [31], he outlines a procedure to examine the feasibility of using semiactive or active vibration isolation instead of purely passive approaches.

Hwang et al. [32] present an interesting method for testing the semiactive damper hardware without using a complete vehicle. They explore the test method known as 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 studies we reviewed deal with the optimization, or the tuning of semiactive suspension systems. Miller [33] explored the effects of the levels of both on-state and off-state damping on the performance of the quarter car semiactive suspension system, while Bellizzi and Bouc [34] and Hrovat, et al. [35] studied optimal control techniques for the semiactive suspension.

More interestingly, several other studies focused on control methods that are able to teach themselves how to control the semiactive suspension system [36-41]. Cheok and Huang [36] and Hashiyama et al. [37] used fuzzy logic and neural network methods to teach the controller, while Frost et al. [38] use a moderated reinforcement learning technique. All three studies show that there are benefits associated with these control approaches. The other three papers [39-41] describe how to apply fuzzy control into designing active or semiactive suspensions.

2.4.2 Keyword: Magnetorheological

The first three studies in the area of magnetorheological fluids deal with characterizing the properties of MR fluids. Lazareva and Shitik [42] 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. [43] 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. [44] 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.

Another three studies explore the design of MR fluid devices. Carlson et al. [6] 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 [45] 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 [46] 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.

One more magnetorheological article by Jolly et al. [47] 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.

Since we have found one paper discussing the modeling magneto-rheological dampers, we will present a literature review related to nonlinear modeling techniques in Chapter 3, which have been developed for other nonlinear devices such as ER fluids.

2.4.3 Keyword: Seat Suspensions

The literature search for the keyword "seat suspensions" yielded only twenty-two articles. Of the twenty-two articles, only five were relevant to this study. In the first article, Ballo [48] 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 that controls vibrations by controlling the airflow 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. Nevala et al. [49, 50] 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 [51, 52] 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.

2.4.4 Keyword: Skyhook

Of the nineteen articles hit using the keyword "skyhook," only four were found to be of relevance. Ivers and Miller [4] and Karnopp [17] contribute an excellent review of many of the past efforts in the area of semiactive suspension design. They also present a very good background of the information that is required to understand semiactive suspension systems. Finally, They discuss 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 et al [28] study the SDOF suspension system and the application of linear quadratic regulator control theory to optimize the suspension in terms of rattle space, 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.

2.4.5 Keyword: Adaptive Control

More than six thousands of publications have contributed to adaptive control. In Sections 1.3 and 2.3, we have discussed various concepts and configurations of adaptive control. Several books have systematically summarize the achievements, [7-9, 20-22]. For brevity, we will only provide a brief summary of the articles that are strongly related to designing adaptive vibration control systems.

Sommerfeldt and Tichy [56, 57] apply the Filtered-X algorithm to design an adaptive controller for a two-stage linear active mount. Both primary and secondary paths are modeled as FIR filters. They introduce an ‘uncoupling filter’ into the system in order to obtain an ideal reference signal. The effectiveness is verified experimentally.

Geng et al [58] develops a feedback adaptive algorithm for linear active vibration systems, which is evolved from the concept of the LMS adaptive filters. In their experiment Terfenol-D actuators are used but their operating ranges are limited in the linear region so that the control system design could avoid the system nonlinearity otherwise existing in large operating ranges.

Baumann [59] also applies the Filtered-X algorithm with the adaptive-Q feedback control to achieve vibration control purpose for linear active systems. The controller doesn't require specific knowledge of the disturbance spectrum or how the disturbance enters the plant.

These control approaches can be further developed for nonlinear systems, even if they are initially developed for linear systems, referred to the next section. In addition, some publications have presented some methods to deal with different nonlinearities in control systems design, [7, 20, 22].

Iserman, et al [7], systematically organize the application of self-tuning regulators to designing adaptive nonlinear systems. It is pointed out that the nonlinear modeling is so complicated that the implementation of such nonlinear adaptive systems can be very difficult. For some situations, it is impossible to use available nonlinear models to represent even simple nonlinearity. Thus, the nonlinear adaptive systems design is still a big field for researchers and engineers to explore.

Tao and Kokotovic [20] systematically deal with the plants with nonlinearity of sensors and actuators such as backlash, dead zone and hysteresis. It is assumed that these three nonlinearities can be modeled in piece-wise linear approximations. But a piece-wise linear assumption is not appropriate for magneto-rheological or electro-rheological devices because their force levels are adjusted continuously subjected to control signals. Thus the design methods they developed are impossible to be applied for our cases.

Widrow and Walach [22] extend the LMS adaptive filter to the development of the adaptive inverse control for linear systems. Some simple examples demonstrate that the LMS adaptive filters can be applied to nonlinear control systems if the controller structure is defined properly. But further systematic research has to be done.

2.4.6 Keyword: Semiactive Adaptive Control

Karnopp and Margolis first described using adjustable dampers to obtain vibration suppression in the wide frequency range. Such systems consume less power and are inherently stable compared to active systems. Semiactive skyhook systems have adaptability, because the damping level can be tuned according to the dynamic system responses such as relative velocity, absolute velocity, and/or relative displacement. Some other researchers try to combine the skyhook control policy with adaptive mechanism to achieve the optimal semiactive control quantitatively, Shoureshi [10], Henry et al [11], Venhovens [12], Boyle et al [13], and Buβhardt [14].

Shoureshi proposes to apply both self-tuning regulator and fuzzy logic control to designing intelligent vibration control systems [10]. Some required preconditions, however, may make implementation difficult, such as linearizing a dynamic system and requiring a reference signal.

In Hery et al's patent, they try to use more available measured signals to tune the damping for a full car suspension. It is a derivative of the skyhook developed in [1]. Different signals reflect different driving situations, thus if the dampers are tuned properly, the design objective can be achieved.

In the Venhovens' and Boyle et al's adaptive semiactive algorithms, some parameters of the suspension systems are required to be known such as mass. Actually the mass is always varying in such as passenger vehicles. It is not practical to have such priori information before the adaptive suspension works every time.

Buβhardt et al and Blankship [15] apply model reference adaptive control (MRAC) to vehicle suspension systems using nonlinear shock dampers. In Buβhardt et al's study, the shock damper is linearized with MRAC approach and the suspension system is designed based on the linear system theory. Blankenship et al assume that the road roughness can be measured as reference signal. Actually this measurement is not only difficult but also expensive if possible.

Finally, we’d like to mention the work that has been done by Rubenstein and Allie [60]. They modify the configuration of LMS adaptive filters to be applicable for semiactive systems. The modified algorithm is a feedforward system, which still requires a reference signal. Further, the plant is modeled using FIR filters. Thus it is limited to (piece-wise) linear systems.

2.5 Summary

A complete overview of the background required for this dissertation was provided. The concepts of magneto-rheological dampers, semiactive control, and adaptive control were reviewed. The results of a detailed literature search were also provided, and the articles that are significant to this study were reviewed.