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**STATE SPACE APPROACH FOR CONTROLLING 1-DOF VEHICLE  
ACTIVE SUSPENSION SYSTEM**

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**May 2007**

“I hereby declare that the thesis is based on my original work except for quotations  
and citations which have been duly acknowledged”



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## ABSTRACT

The advantages of an automotive active suspension system have been promised for many years. A fully active suspension based on hydraulic actuators seemed to be a good candidate for fulfilling such expectations. However the high frequency characteristics of such systems have been proved to be problematic for practical implementations. A high fidelity mathematical model capturing realistic dynamic behaviors of the hydraulic active suspension is required for the development of such systems. An appropriate active suspension control overcomes this tradeoff and provides maximum ride comfort and road holding quality within the available suspension travel. In this project, state space approach have been chose for the method in modeling the suspension and designing the controller to improve the performance of active suspension system.

CHAPTER		PAGE
	<b>ACKNOWLEDGEMENT</b>	i
	<b>ABSTRACT</b>	ii
<b>1</b>	<b>INTRODUCTION</b>	1
	1.1 Project Title	1
	1.2 Objective	1
	1.3 Project Scope	1
	1.4 Project Significant	2
	1.5 Project Flow Chart	3
	1.6 Suspension	4
<b>2</b>	<b>LITERATURE REVIEW</b>	8
	2.1 Active Suspension	8
	2.2 Important Of Suspension	10
	2.3 Suspension Control System	11
	2.4 Suspension Controller Design Method	12
	2.5 Controllability and Observability	15
<b>3</b>	<b>METHODOLOGY</b>	19
	3.1 Introduction	19
	3.2 State Space	20
	3.3 MATLAB	21
<b>4</b>	<b>MODELLING</b>	22
	4.1 Dynamic Equation	22
	4.2 Simulation	26
	4.3 Controller Design	39
	4.4 Controller Simulation	50
<b>6</b>	<b>CONCLUSION</b>	60
<b>7</b>	<b>REFERENCE</b>	61

# CHAPTER 1

## INTRODUCTION

### 1.1 Project Title

- State Space Approach For Controlling 1-DOF Vehicle Active Suspension System

### 1.2 Objective

- Observation on active suspension system
- Designing the controller by using the state space approach
- Find the improvement of the suspension after using the controller

### 1.3 Project scope

- Literature Review
- Mathematical model of the suspension system
- Form mechanic properties from the mathematical equation
- Study on the method of state space
- Form the state space equation
- Study on the method for controller design
- Designing the controller
- MATLAB study
- Simulate the system using MATLAB
- Analyze and find the characteristic of the system

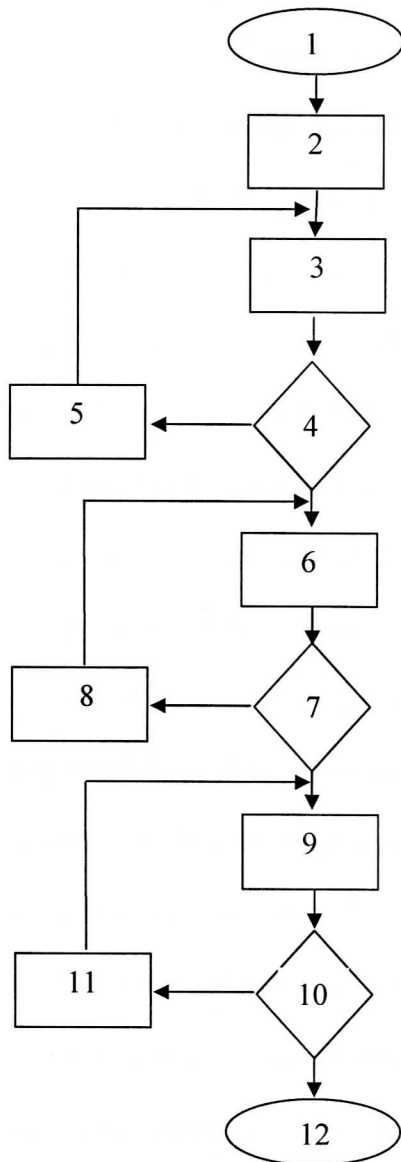
## **1.4 Project Significant**

The main objective of this project is to improve the performance of the vehicle active suspension system. This come from the controller that will be design in this project. The controller will improve the performance of the suspension and this controller is design by using the state space approach.

In automotive industries now day, the performance of the vehicle is the most importance thing that been focus. It include the comfortable of passenger, security and many other things. This suspension system is refer to the comfortable of the passenger. In order to improve this needed, many kind of controller have been approach. This project is trying to develop a controller for this active suspension system in order to improve its performance.



## 1.5 Project Flow Chart



1. Start
2. Briefing from supervisor
3. Planning for the proposal
4. Consideration from the supervisor
5. Correction
6. Project development
7. Project result
8. Result analysis
9. Draft submission
10. Checking
11. Correction
12. Submit

## 1.6 Suspension

The suspension of vehicle is directly related to the comfort of the drive and the handling of the car. A car can be set up for either comfort or for handling. It is very tricky to get a vehicle set up to be both a very smooth, comfortable ride and to handle like a sports car. The suspension system is part of your vehicle chassis. Other main parts of an auto chassis are the frame, steering and tires. The suspension is the system that supports the weight of the vehicle as well as absorbs and dampens energy from road shocks while it helps to sustain tire contact to the road.

When thinking of an auto suspension, probably first think of shock absorbers. It is nice that the name actually explains what these parts do. It take up some of the shocks, the bumps and potholes, which a roadway places on vehicle. In reality shock absorbers handle the abuse produced by the rebound of your cars springs. Coil or leaf springs actually handle the abuse from the road. So the combination of both the coils and the shock absorbers is what helps keep car under control. These two parts are vital to cars suspension so we will look at them more in-depth.

There are different types of springs. The coil or leaf springs is the most widely used type. Coil springs are the type that most people picture when bring up springs[1]. It compress and expand to absorb the abuse of the wheels hitting pavement. Coil springs look like a stiff pulled-out Slinky.

The leaf spring was popular in the 1980s and now is mostly used only on trucks and sport utility vehicles. This type of spring is made up of several tiers of metal, named leaves, which are fastened together so that it perform as a single entity.

Vehicles with tightly wound springs are the sports cars that are built for handling. It is stiff to ride in and feel more bumps on the road but they minimize the

body movement of the automobile and drive it more aggressively. This differs from loosely wound springs. These types of springs have a lot more give when hit potholes or drive on a bumpy road but do not handle as well as cars with tightly wound springs.

Springs are built to absorb energy but not to dissipate it. The part that is built for that function is the shock absorber. A shock absorber can also be called a dampener. Without this dampener the springs would bounce to take in the energy and then continue to bounce and bounce until the energy was dispersed. This would cause a very bouncy, uncomfortable ride. The shock absorber controls that bouncing movement by dampening it[1].

A shock absorber is like a small oil pump that is placed between the vehicle wheels and frame. One of the most common styles of shock absorbers is called the twin tube design. There is an upper mount attached to the frame and a lower mount attached to the axle near the wheel. The upper mount transfers the energy of the spring to the shock absorber after car hits a bump on the roadway. This transference continues through cycles called the compression and extension cycles until the energy is dissipated.

Though shock absorbers and springs are essential to an auto suspension it are not the only components that make up suspension. The remaining main parts of a suspension system are the struts, anti-sway bars and tires.

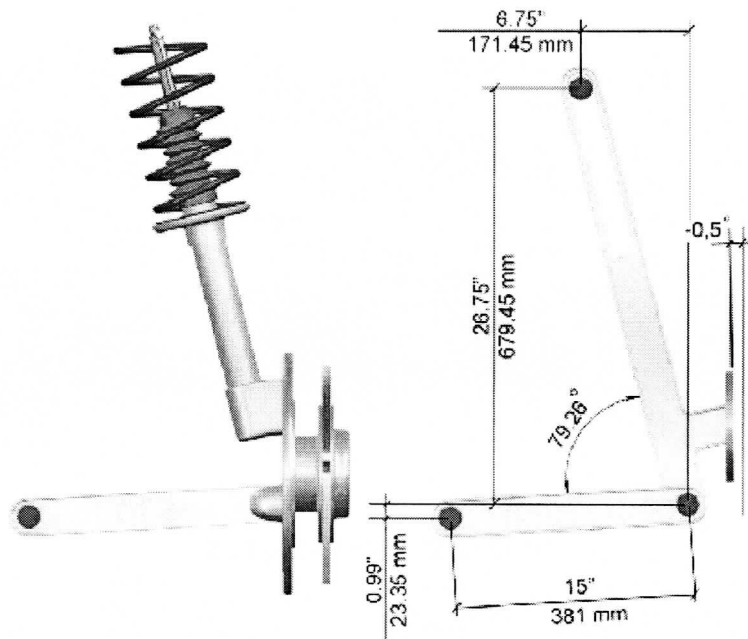
Most vehicles have what is called a strut suspension system. A strut system brings together the coils and shock absorbers of a conventional system and places into one unit. This does away with the need for many other parts. With fewer parts to the strut system there are fewer parts to break or replace during the ownership of the vehicle.

Due to the design a strut system is lighter and takes up less space. The strut functions in two essential ways[1]. The struts perform as a dampener, similar to the shock absorber as well as providing structural support for the automobile suspension. The result of a strut system should be a smoother ride and better handling. Struts can affect the tire alignment and actual tire wear on your car as well.

Anti-sway bars are what transfers movement to the tires. Their purpose is to stabilize the vehicle. An anti-sway bar is the technical name for a metal rod that extends across the axle and joins each side of suspension together. When the suspension at one side (wheel) moves up or down the bar transfers the movement to the other side (wheel). This transference allows for a more balanced ride and reduces the roll of the vehicle chassis.

Tires are the final suspension component. Tires are part of the suspension system because they must be in good working order for the suspension to work properly. The suspension system function is to capitalize on the friction between the roadway and vehicle tires. It is the friction between the tires and the roadway that affects the auto ability to accelerate, brake and steer properly. Tires that are worn down or improperly inflated can hinder the suspension system from functioning correctly.

This only a brief description of the most common parts of a suspension system. There might be more parts in vehicle suspension depending on the type of car, if it is front or rear-wheel driven. Improvements and new developments are always occurring so the vehicle might be even more advanced. The best way to find out about vehicle particular suspension is to find a model specific book written about vehicle.



**Figure 1** Suspension Model (courtesy of M. Appleyard and P. E. Wellstead, Mar. 1995)

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Active Suspension

The active suspension provides the best performance but the cost is high. On the other hand, the passive suspension system is less in cost but provides low performance. The semi-active suspension can provide a good performance in low cost. The performance of a vehicle suspension system is typically rated by its ability to provide improved passenger comfort and to avoid hitting its suspension travel limits[2]. Current automobile suspension systems using passive components can only offer a compromise between these two conflicting criteria by providing spring and damper coefficients with fixed rates.

3 kind of suspension system that are :

- Passive Suspension System
- Semi-Active Suspension System
- Active suspension System

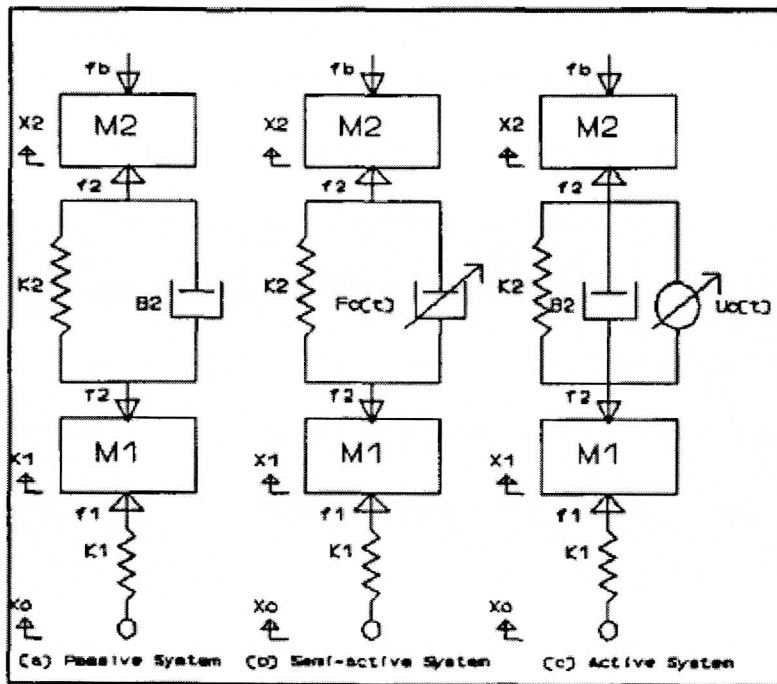


Figure 2 Passive, Semi-Active and Active Suspension System(courtesy of Jung-Shan Lin, June 1997)

Active suspension systems move each wheel up and down to control body motion in response to road abnormalities. The system responds to inputs from the road and the driver. With an active suspension, a vehicle can simultaneously provide the smooth ride of a soft suspension along with superior handling associated with a firm suspension.

Most active suspension systems use a high-pressure pump with hydraulic cylinders at each wheel to position the wheels with respect to the vehicle. Up and down motion of the wheels is actuated by electronically controlled valves[3]. Other alternatives to power active suspension systems include electric motors or electromagnets. In any system, sensors at each wheel determine vertical wheel position

and the force of the road acting on the wheel. Some systems use road preview sensors (radar or laser) to provide information about road abnormalities before the front wheels reach them. Accelerometers tell the computer when the vehicle is accelerating, braking or cornering. The computer uses complex algorithms to continuously process information and decide the position of each wheel. Coil springs can be used at each wheel to avoid bottoming out of the suspension in case of system failure. It also can reduce the power required to support the sprung weight of the vehicle. Customer benefit here are outstanding ride and handling, even on rough roads.

The key characteristic of the active suspension system is that an external power source is used to achieve the desired suspension goal. The controller drives the actuator based on the designed control law[4].

## **2.2 Important Of Suspension**

In active suspension design, the primary goal is to resolve the inherent tradeoffs between ride quality, handling performance, suspension travel and power consumption[2]. The main function of suspension is to reduce the vertical acceleration of the car body. This increases the likelihood of hitting the suspension travel limits when driving over a speed bump or into a pothole, which causes not only considerable passenger discomfort but also increased wear and tear of vehicle components[2]. Suspensions should have the ability to behave differently on smooth and rough roads, the desired response should be soft in order to enhance passenger comfort, but the suspension should stiffen up to avoid hitting its limits when the road surface is too rough.



The ride comfort is corresponding to the axis and angular acceleration of the front and rear of car body to minimize the numerical body axis and angular acceleration equals to require higher quality of ride comfort[4]. In addition, suspension travel means the space variation between body and tire. The nonlinear back stepping controllers with two additional nonlinear filters are proposed to enhance ride comfort of passengers for a half-car active suspension design

### **2.3 Suspension Control System**

The suspension control system incorporates an accelerometer measuring body vertical acceleration and a displacement transducer measuring the relative displacement between the suspension and the body. These signals, together with a signal measuring pressure in the unit, are fed to the electronic processing unit. An engine driven swash plate axial piston oil pump supplies the system pressure and peak demand flows are met by the accumulator. Output from the electronic processing unit is fed to the three-way flow control valves one, for each wheel.

A vehicle suspension system comprising fluid cylinders connected between the vehicle body and the respective wheels. A fluid control system which controls feed and discharge of hydraulic fluid to and from the fluid cylinders and changes the suspension properties of the suspension system[3]. A failure detecting means which detects a failure in the fluid control system. A measure mode determining means which receives a signal from the failure detecting means and determines which of first to third measure modes is to be taken on the basis of the kind of the failure represented by the signal, warning being just given and the control of feed and discharge of hydraulic fluid to and from the fluid cylinders being continued when the first measure mode is taken, the control of feed

and discharge of hydraulic fluid to and from the fluid cylinders being interrupted with the chassis height fixed to the present height when the second measure mode is taken, and the fluid in the fluid cylinders being discharged and the chassis height being lowered when the third measure mode is taken; and a performance means which receives a signal from the measure mode determining means and performs the measure mode determined by the measure mode determining means.

An anti-squat suspension control system includes an anti-squat control disabling means for disabling anti-squat control for a period while an engine idling condition detector switch is held closed or a given period after the engine idling condition detector switch is switched from closed position to open position. The system also includes fail detector means for monitoring operation of the engine idling condition detector switch to detect failure of the switch. When the failure of the engine idling condition detector switch is detected, the anti-squat disabling means is disabled.

A suspension control method for controlling suspensions equipped with variable damping force shock absorbers. First, an ideal movement pattern for restoring the sprung mass from a local highest or lowest position to a neutral position is previously determined. After the sprung mass has attained its local highest or lowest position, the control amount for altering the damping force of the shock absorber is successively calculated so that the sprung mass actually follows the ideal movement pattern[4]. As a result, the sprung mass in its local lowest or highest position can swiftly returned to the neutral position in a semi-cycle.

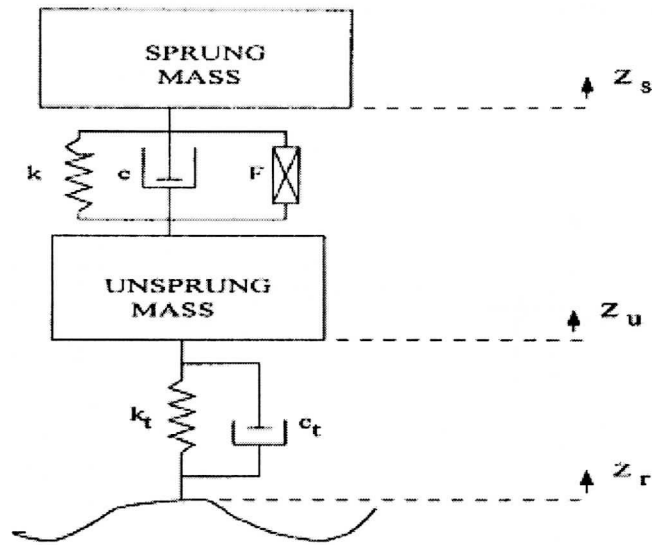
## 2.4 Suspension Controller Design Method

The nonlinear back stepping schemes are one of the method employed to design the controller for an active suspension systems. The control objectives here are not only to minimize the displacements of the front and rear body for improving ride quality, but also to prevent suspension travels from hitting their travel limits.

To verify that nonlinear control design achieves the desired objectives, the simulation for the resulting closed-loop system with nonlinear filters (solid line) and compare it to both a passive suspension system and an active suspension design with the front and rear linear filter must be done.

Model Predictive Control (MPC) design is one of choice for control of active suspension systems utilizing previewed road information. MPC design explicitly incorporates all hard constraints on state, control and output variables[4]. It generalizes the approaches based on feedback linearization and dynamic inversion from single step control to multiple step control over a receding prediction horizon.

Model Predictive Control (MPC) to address the issues of control saturation, nonlinear dynamics, on-line adaptation and failure accommodation. The overall objective is to demonstrate the advantages of using the MPC methodology for Active Suspension using Preview information[5]. In fact, it is very natural to use MPC design for this problem since it is explicitly based on the prediction of system response over a finite future horizon using all available information, including measurement of disturbances.



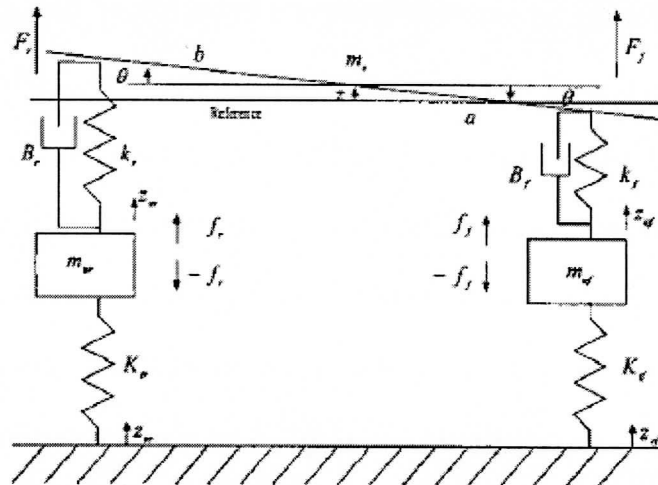
**Figure 3** Suspension System Model(courtesy of K. Mehra, October 1997)

The two degrees of freedom quarter car model is the most commonly used model in controller design studies for active suspensions. The equations of motion for the model are found by adding vertical forces on the sprung and un sprung masses. For this project, it only use the one degree of freedom.

Active suspension control approach also designed for a quarter-vehicle suspension system using a filtered feedback control scheme and a novel compressible fluid suspension system[6]. Analysis of feedback for the mechanical subsystem shows that motions of the sprung mass above and below the wheel frequency can be mitigated using skyhook damping plus active filtering of spring and damping coefficients.

Many control approaches have been investigated such as optimal control, back stepping control and nonlinear control. It is well known that motions of the sprung mass

at the wheel frequency cannot be reduced if only control input is a force applied between the Sprung and unsprung masses .



**Figure 4** Half-car Model Suspension System(courtesy of A. J. Truscott, Dec 1993)

## 2.5 Controllability and Observability

Controllability and observability represent two major concepts of modern control system theory. These originally theoretical concepts, introduced by R. Kalman in 1960, are particularly important for practical implementations[9]. It can be defined as follows. Controllability mean in order to be able to do whatever we want with the given dynamic system under control input, the system must be controllable and observability mean in order to see what is going on inside the system under observation, the system must be observable. Even though the concepts of controllability and observability are almost abstractly defined, now intuitively understand their meanings. The remaining problem is to produce some mathematical check up tests and to define controllability and

observability more rigorously. The observability of linear discrete systems is very naturally introduced using only elementary linear algebra.

Controllability is an important property of a system to be controlled. A linear controllable system may be defined as a system which can be steered to any state from the zero initial state. For example, if the linear system is a circuit consisting of capacitors, inductors, and resistors controlled by an external voltage, then controllability means that by varying in time the external voltage, can achieve at some point in time any combination of voltages on capacitors and currents through inductors. The controllability property plays an important role in many control problems, such as stabilization of an unstable system by feedback, or optimal control.

Since the output is a linear combination of the input and states, one or more poles can be canceled by the zeros induced by this linear combination. When that happens, the canceled modes are said to be unobservable. Of course, since started with a transfer function, any pole-zero cancellations should be dealt with at that point, so that the state space realization will always be controllable and observable. If a mode is uncontrollable, the input cannot affect it; if it is unobservable, it has no effect on the output. Therefore, there is usually no reason to include unobservable or uncontrollable modes in a state-space model

The fundamental controllability problem is associated with the question whether an input can be found such that the system states can be steered from an initial value  $x_0$  to any final value  $x_1$  in a given time interval. In general, the answer to this question depends on the time interval. This induces different notions of controllability all of

which become equivalent for linear time invariant systems. In the following discussion, only this simpler case is considered.

Kalman's canonical decomposition provides the basic theory and computational algorithm to remove unnecessary states from a realization, while preserving the input-output map[9]. Its reliance on the controllability and observability matrices makes the approach somewhat susceptible to numerical problems, as these matrices are often poorly conditioned. A more serious drawback, however, is that this reduction is based on structural properties of the system (linear independence) but without explicitly considering the quantitative aspects of the problem. In practical applications, especially when numerical computations are involved, one is rarely faced with perfectly dependent or perfectly orthogonal vectors. Moreover, a commonly encountered problem is that of a model reduction where modes that have independent but small contributions should be eliminated. With such an objective in mind, the previous algorithm is inadequate.

The conclusion that can be made here are active suspension with preview provides significant improvement in system performance over a purely passive suspension system. More realistic hardware modeling such as actuator valves and sensors would be the next step in the development. Also in practice there are a number of nonlinearities which need to be considered in the model such as flow rate limits in control valves[7]. The further developments in the controller are mainly in the application of more sophisticated controller algorithms. Further improvements in performance can be obtained by correlating the front and rear wheel inputs in the full car model. This is where the front wheel disturbances can be used as preview information for the rear suspension controllers to provide further comfort in the back seat[8].

There are two main factors which determine the overall performance of a suspension. Its handling capability is the performance under the dynamic loads experienced during cornering and braking. This gives rise mostly to low-frequency dynamics. The suspension ride performance is its response to an uneven road surface in which high frequency dynamics, arising from the wheel motions, play a large part. There are often design conflicts between the requirements of good handling and ride in suspensions.