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Research and Simulation on New Active Suspension Control System

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Research and Simulation on New Active Suspension Control System

by

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ABSTRACT

Suspension system is the most significant part which heavily affects the vehicle handling performance and ride quality. Because of its structures limit, the passive suspension system can hardly improve the two properties at the same time. Since the advent of active suspension system, it has become the research hot spot. The design of the control strategy is the core of active suspension system technology. So the research of the application of new algorithm and pavement feedback in automobile active suspension spreads out in this thesis.

According to the automobile suspension system dynamic characteristic, this thesis use modern control theory in the active suspension system. The author puts forward new control strategies: new algorithm and pavement feedback, and combined with PID control, which make active suspension system control performance further improve.

The author uses the vehicle kinematics theory to set up active suspension system dynamic model. The author also established integral white noise form of pavement input mathematics and simulation model. Through the Simulink software, simulation model was constructed. It achieved the control simulation with different input of the active suspension system.

Through the analysis of simulation results, we know that new algorithm and pavement feedback control strategies are more reasonable and feasible. The combination of PID control and new algorithm is more competitive, it has shown best stability and reliability. This combination also greatly improves the displacement and acceleration characteristics, and the curve is more smoothly, which achieved great effect.

This new type of intelligent control strategy provides a new thinking way for the automotive active suspension control theory.

CHAPTER 1 PREFACE AND INTRODUCTION

1.1 Problem Description

Suspension system is the most significant part which heavily affects the vehicle handling performance and ride quality. Traditional suspension systems use a combination of sets of springs and sets of dampers to decrease the vehicle vibration. The passive suspension system, which has the largest amount equipped on current vehicle, its spring and damper coefficient is constant and cannot adjust itself along with its road surface situation, so the active suspension system, which can automatically create restoring force to maintain the vehicle steady, have taken to the stage. The active suspension system involves numerous complex technical problems, such as mechanology, electronics and materials science, but this thesis is focused on its control systems and control methods, rather than discuss the other aspects. Our problem is proposed that how could we control an active suspension more effectively and react accurate with the change of road surface roughness, so that to make the people in the vehicle feel comfortable and steady, also protect the vehicle components from heavy vibration to extend its working life. [1]

1.2 Research Purpose and Meaning

At present, the world's major automotive companies and research institutions have invested considerable human and material resources to develop cost-effective vehicle suspension system, in order to be widely used on the vehicle. To this end, using the new control technology, research and development to a control system, which is effective, low energy consumption and low cost, is not only an important goal of applied research, but is bound to be an important evaluation criteria to determine the theoretical research is valuable. Therefore, excellent research of vehicle active suspension system is bound to be the future direction of the vehicle suspension development. [2]

As the vehicle speed increases, the performance of the passive suspension systems limits the further improvement of the performance of the automotive. The requirements, which directions to high value-added, high-performance and high-quality development, of modern automotive suspension is not only to ensure its basic performance, but also committed to improve driving safety and comfort of the vehicle. Electronics, sensor technology is in rapid development. Microcomputer, as the representative of electronic equipment, has significant improvements in performance and reliability, so that further improve automotive electronic devices, which improve the reliability, cost reduction, reducing the volume. And electronic control technology is effectively used in various parts, including the suspension system. Because of the use of electronic technology to achieve the control of the vehicle suspension system, the vehicle comfort performance can reached a satisfactory level, and the vehicle handling and stability to achieve the best state. [3]

For vehicle active suspension system, the study of the appropriate suspension control technology is the key to improve its performance. This paper purpose is to research and test different control methods, which can adapt to different road surface roughness, based on modern control theory. And I will find one or a combination of these control methods, which is the most effective way.

The vehicle suspension performance is an important factor affects the vehicle ride, handling, stability and speed. Therefore, the study of vehicle vibration, design new suspension systems, and control vibration to low levels are important measures to improve vehicle quality. [4]

1.3 Main Contents and Research Methods

The research object in this paper is the active suspension system; Mathematical and simulation model of the passive and active suspension systems are established; research on some control methods of the active suspension system, and use Simulink to get the time domain results. The main contents and methods of research include:

1. Use kinematics and dynamics to establish the mathematical model of the passive and active suspension of a quarter two degrees of freedom and did its stress analysis. Establish mathematical differential equations and state-space matrix expression.

2. Select the road input signal-unit step signal, sine wave signal and white noise signal. Build road input mathematical model and simulated in Matlab/Simulink.

3. Propose some the active suspension control type- PID control, Pavement feedback control and a new algorithm. Regulate parameters of the systems.

4. Use Matlab/Simulink software, based on the mathematical equations of the suspension force, established computer simulation model of the passive and active suspension systems.

5. Combine modules of the model above; make several different sets of suspension simulation system as a combination of the road input - passive suspension system, and road input - PID Control active suspension system.

6. Input the above simulation system parameter, and then run the simulation system, which can draw the curve of the desired output, and output its qualitative and quantitative comparative analysis of the conclusions.

CHAPTER 2 OVERVIEW OF SUSPENSION SYSTEMS

2.1 Suspension Type and Performance

According to the control principle and control functions, the suspension system can be divided into passive suspension, semi-active suspension and active suspension, these suspension system is very different in the performance aspects.

2.1.1 Passive suspension

Figure 1 shows a typical type passive suspension system. Passive suspension cannot change stiffness and damping coefficient, and it has no additional power and actuator. It consists of springs, dampers and oriented institutions. Passive suspension is the traditional mechanical structure. It has simple structure, reliable performance, low cost and no additional energy, which is currently the most widely used on the vehicles. Passive suspension cannot adjust stiffness and damping, according to the random vibration theory, it can only ensure the specific operating conditions to achieve optimal damping effect, it is difficult to adapt to different road and tough use; while taking passive suspension is also difficult to acquire good ride comfort and handling stability at the same time, because these two requirements is a pair of contradiction. [5]

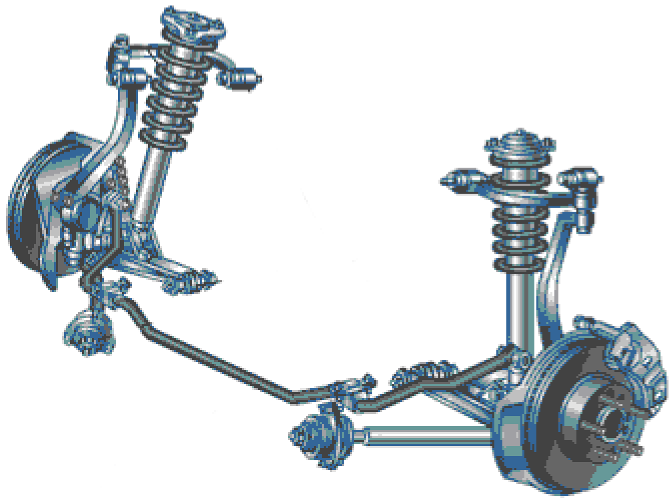


Figure 1 - Typical type passive suspension system

Due to the structure itself, the traditional passive suspension summed up in the following defects:

1. Due to the suspension travel stroke and is inversely proportional to the square of the system natural frequency, when the frequency is reduced, it has prone to large travel stroke;

2. The suspension components are limited by the stiffness and damping, which restricts the range of its parameters;

3. Suspension system parameters are fixed and cannot meet the load, road conditions, speed and other changes in circumstances.

Passive suspension is mainly used in middle and low end cars. Research to improve the passive suspension performance hit in three aspects: First, how to find the optimal suspension parameters, mainly through modeling and simulation; Second, gradient stiffness springs and mechanical variable-damping shock absorbers, so that suspended frame parameters to adapt to different conditions within a certain range; The third, suspension-oriented institutions, in this area focus on the multi-link suspension with stabilizer bar. [6]

2.1.2 Semi-active suspension

Semi-active suspension is one of the suspensions that elastic element stiffness and shock absorber damping can adjust according to the need for regulation and control. Skyhook semi-active suspension concept was proposed in1974. The spring stiffness adjustment is relatively difficult, so semi-active suspension mainly by regulating the shock absorber damping.

Semi-active suspension system has no specifically dynamic control components. It passed the velocity sensors data to the vehicle ECU controller to calculate the required control force, and then adjust the shock absorber damping to attenuate vibration of the vehicle body. The study of semi-active suspensions are also focused on two aspects, one is the research on actuator, which is the damping adjustable shock absorbers; the other hand, the control strategy. Magnetorheological damper is the semi-active suspension latest technology and lots of researchers show great interests on this new technology. It has a quick response, which is lower than 1ms.

Semi-active suspension system also has its own advantages, such as its devices volume and cost is greatly lower than the active suspension system, but this paper is mainly focused on the active suspension system, so it do not need to take a big space to discuss this kind of the suspension. [7]

2.1.3 Active suspension

With ever-increasing demands on vehicle performance and speed in modern society, more and more refined manufacturing techniques of mini-computer, as well as sensors, microprocessors and other electro-hydraulic control components, gave birth to the vehicle active suspension. The automotive active suspension, according to road conditions and vehicles load, controls their own working status. Active suspension need to take effective control strategy to make the suspension to achieve the performance required to achieve, therefore, the choice of control strategy for controllable suspension has a great influence of performance. [8]

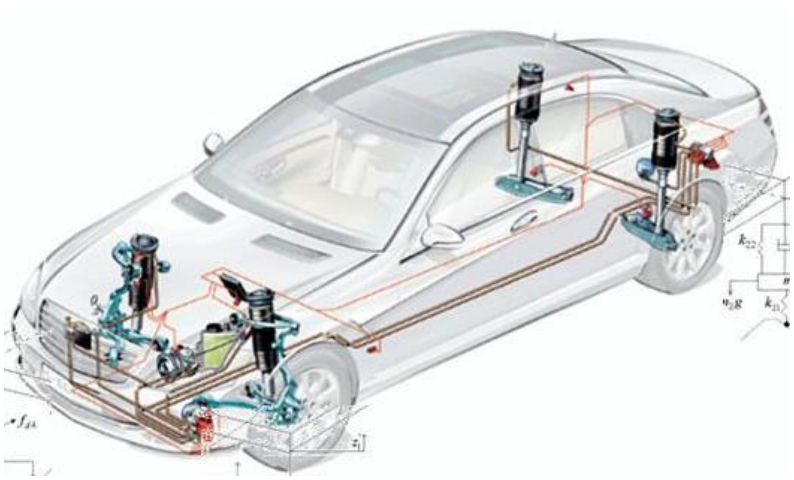


Figure 2 - Active suspension system schematic diagram

Active suspension is a new computer-controlled suspension with three conditions: (1) power source capable of generating the force; (2) the implementation of components to pass such a force and can work continuously; (3) has a wide variety of sensors and the data set to microcomputer operations and determine the control mode. Therefore, the active suspension brings together the technical knowledge of mechanics and electronics, is a more complex high-tech device. In addition, the active suspension is to control body movement. When the car is braking or turning, inertia will generate caused by the spring deformation, active suspension will produce an inertia force against this force, to reduce the changes of body position. [9]

2.2 Performance Comparison of Three Type Suspensions

Suspension system type	**Passive suspension system**	**Semi-active suspension system**	**Active suspension system**
Regulatory element	General shock absorber	Adjustable damper	Hydraulic system or Servo motor system
Action principle	Damping constant	Damping continuously adjust	Adjust the force between wheel and vehicle body
Control method	No	Electronic-hydraulic automatic	Electronics or magnetic or fluid control

Bandwidth	Unknown	Up to 20Hz	>15Hz
Energy consumption	Zero	Very small	Big
Lateral dynamics characteristics	No	Middle	Good
Vertical dynamics characteristics	No	Middle	Good
Cost	Lowest	Middle	Highest

Table 1 - Performance Comparison of Three Type Suspensions

CHAPTER 3 VEHICLE SUSPENSION MATH MODEL

3.1 Passive Suspension Math Model

Vibration control system design should start with the establishment of mathematical model of the system, and then determine the design requirements, and formal description of it. And then select one or several design methods to design the control system, and further attached to simulation or model experiments to identify the control system is designed to meet the performance requirements. Therefore, the establishment of the mathematical models of the system is a prerequisite for the entire control designs and control system design is closely related to the control system quality evaluation model. [10]

As with other engineering control system, a mathematical model of the suspension control system refers to the formal model, for short the mathematical model. Such models typically rely on the known laws (this article by means of dynamic principle) to be derived or through some of the system dynamics test. Then it experiences mathematical simulation and optimization, or statistical approach. The key to create a system of mathematical models is to provide a description of the model form and determine its parameters.

In vibration control area, there are three kinds of models most popular to describe the form, the state space description, transfer function description and weight function description. In accordance with the implementation of continuous control and discrete control of different characteristics, they are each divided into a time continuous and time discrete mathematical description.

The automotive is a complex vibration system, should simplify based on the analysis of the problem. Simplification of motor vehicles there are several ways, but according to the convenience of the study, in this paper we simplify it into a system model as shown below:

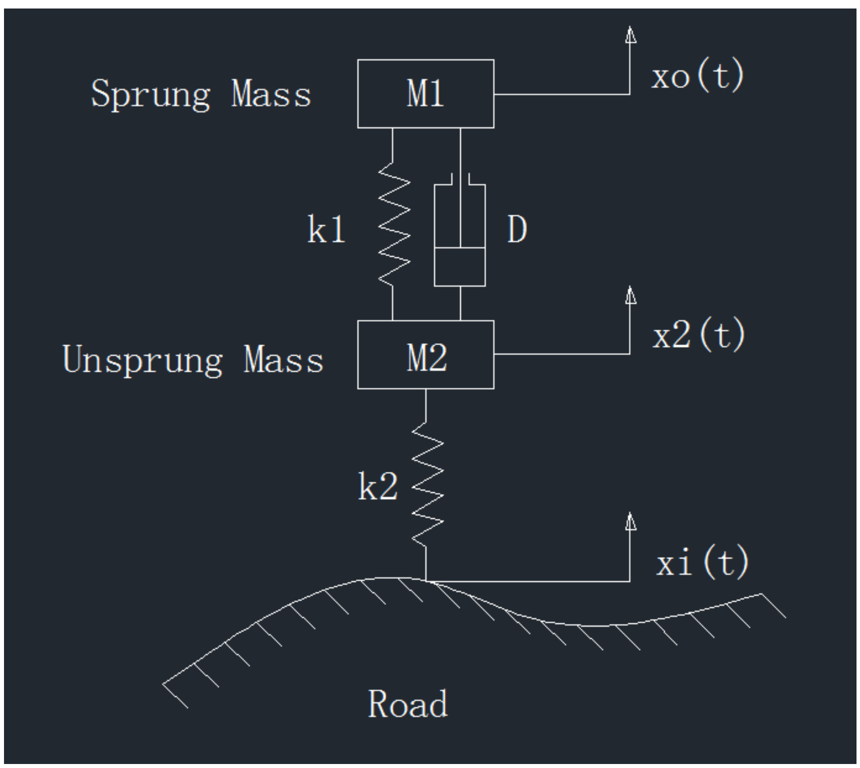


Figure 3 - ¼ Math model of passive suspension system

Figure 3 shows a quarter vehicle model of the passive suspension system. The sprung mass M_1 represents the vehicle body, and the unsprung mass M_2 is an assembly of the axle and wheel. The tire is assured to contact the surface of the road when the vehicle is traveling, and is modeled as a linear spring with stiffness k_2. The linear damper, whose average damping coefficient is D, and the linear spring, whose average stiffness coefficient is k_1, consist of the passive component of the suspension system. The state variables $x_o(t)$ and $x_2(t)$ are the vertical displacements of the sprung and unsprung masses, respectively, and $x_i(t)$ is the vertical road profile.

This is a vehicle body and wheel dual-mass vibration system model. From this model, we can analyze the vehicle suspension system dynamics and establish two degrees of freedom motion differential equations. Their equilibrium position is the origin of coordinates; we can get the equations as follow (3.1) and (3.2) [11]:

$$m_1\ddot{x}_o(t) + D[\dot{x}_o(t) - \dot{x}_2(t)] + k_1[x_o(t) - x_2(t)] = 0 \tag{3.1}$$

$$m_2\ddot{x}_2(t) - D[\dot{x}_o(t) - \dot{x}_2(t)] + k_1[x_2(t) - x_0(t)] + k_2[x_2(t) - x_i(t)] = 0 \tag{3.2}$$

If we make a Laplace transformation to the above equation, we can get equation (3.3):

$$\frac{X_o}{X_i} = \frac{k_2(Ds + k_1)}{M_1M_2s^4 + (M_1 + M_2)Ds^3 + (M_1k_1 + M_1k_2 + M_2k_1)s^2 + Dk_2s + k_1k_2} \tag{3.3}$$

The above equation is the passive suspension system transfer function, if we use Matlab/Simulink Transfer function module, the reference is as below:

NUM= [0, 0, 0, k2*D, k1*k2];

DEN=[m1*m2,(m1+m2)*D,m1*k1+m1*k2+m2*k1,k2*D,k1*k2];

¼ model of passive suspension system can simulate the vehicle suspension system when it drives on the road. It can better shows the influence which make by springs and damping of the suspension system.

The following figure 4 is an example unit step response by using this math model. It shows the suspension system's $x_o(t)$ react with the time when the vehicle get through a pavement uplift.

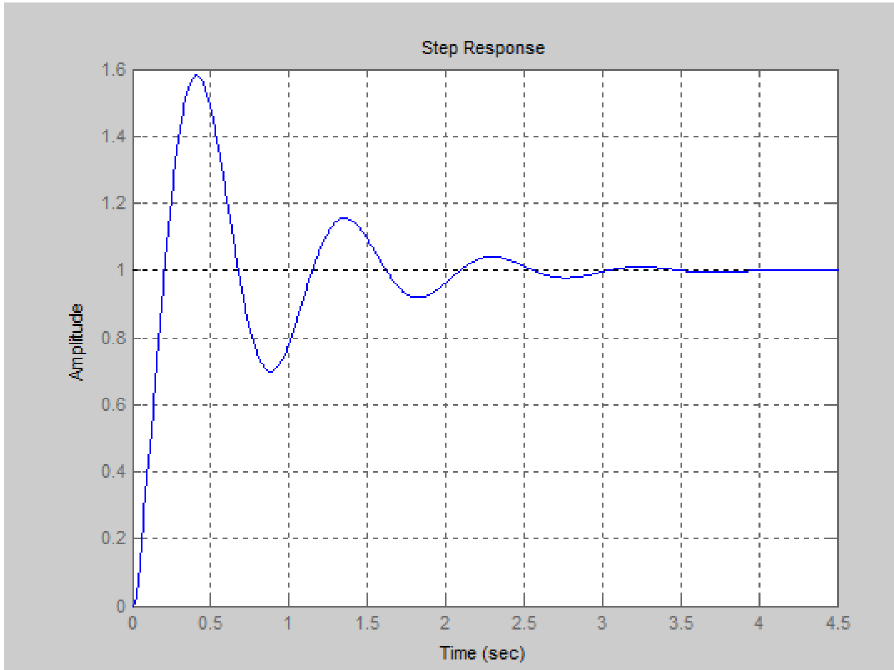


Figure 4 – The passive suspension time domain response with unit step signal

The following table shows the each vehicle model parameter symbol, numerical value and unit:

Vehicle Model Parameters	Symbol	Numerical Value	Unit
Sprung Mass	M_1	300	kg
Unsprung Mass	M_2	40	kg
Suspension Stiffness	K_1	15000	N/m
Tire Stiffness	K_2	150000	N/m

Suspension Damping Coefficient	D	1000	N*s/m

Table 2 - Vehicle ¼ passive suspension model simulation input parameters form

3.2 Active Suspension Math Model

The mathematical model and the simulation made by following chapters are only discussing the amount of force created by the active suspension, and are not discussing what kind of active suspension system and how does the active suspension created force.

Most of the researchers chose to use ¼ vehicle dynamic vibration model when they focus on the vehicle body vertical vibration caused by the input of pavement roughness. Although ¼ vehicle dynamic vibration model has not included the entire vehicle geometrical information, and it cannot research the vehicle pitching angle vibration and roll angle vibration, but it has nearly included most of the essential feature, such as the change of the load and suspension system's stress information. A suspension system can be simplified as ¼ vehicle dynamic vibration model when we consider the following characteristics [12]:

(1) The front suspension system and the rear suspension system are independent of each other;

(2) Research Emphasis on the suspension itself and the affect caused by the tire.

(3) All the elastic components can be considered to simplify as springs and damping.

(4) Decrease the system parametric description under precondition of keeping accuracy and effectiveness;

(5) Actuator can only output force. No consideration of actuator's mass.

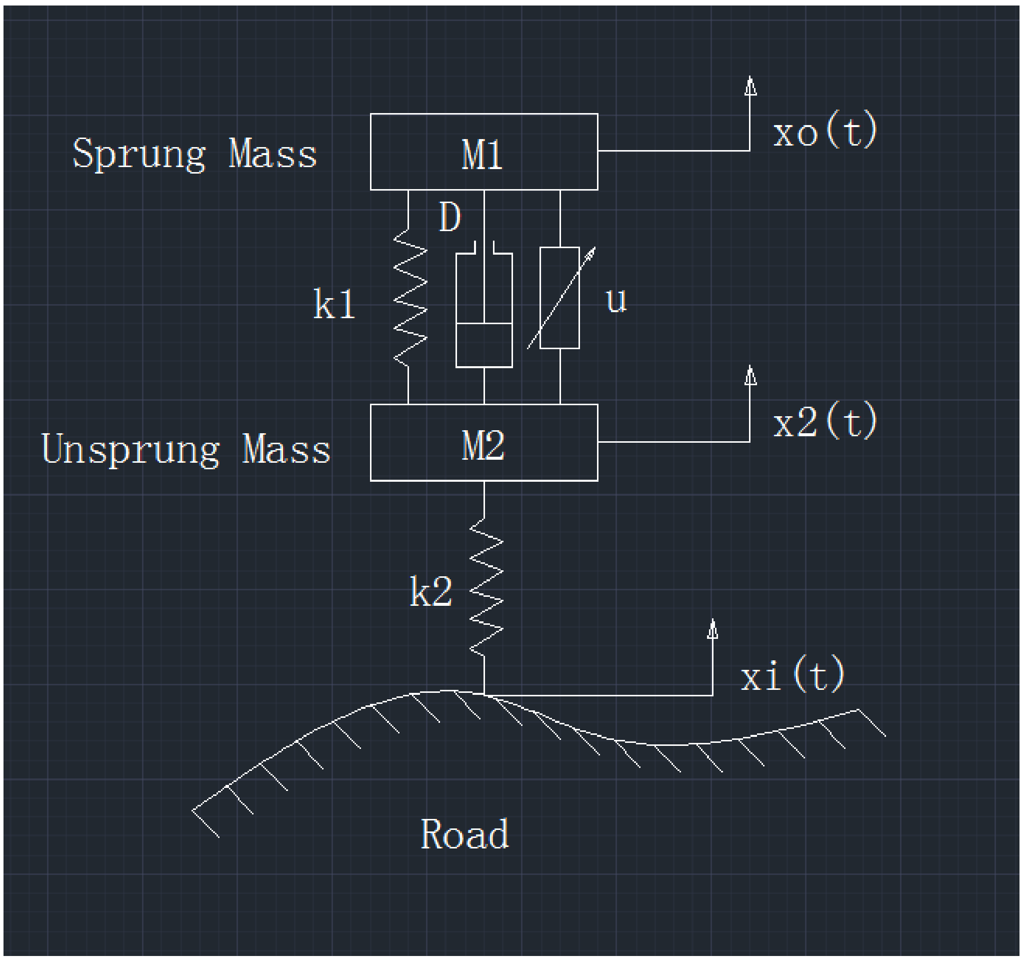


Figure 5 - ¼ Model of active suspension system with actuating force (u) between sprung and unsprung mass.

According to the above assumption, figure 5 shows a vehicle ¼ model of active suspension system, the parameters M_1, M_2, K_1, K_2, D, $x_i(t)$, $x_o(t)$, $x_2(t)$ represent as same as in the passive suspension model, while u is the active control force, which created by the active suspension actuator.

From this model, we can analyze the vehicle suspension system dynamics and establish two degrees of freedom motion differential equations as follow [13]:

$$m_1\ddot{x}_o(t) + D[\dot{x}_o(t) - \dot{x}_2(t)] + k_1[x_o(t) - x_2(t)] = u \tag{3.4}$$

$$m_2\ddot{x}_2(t) - D[\dot{x}_o(t) - \dot{x}_2(t)] + k_1[x_2(t) - x_0(t)] + k_2[x_2(t) - x_i(t)] = -u \tag{3.5}$$

We can set:

$$x_1 = x_2(t), x_2 = x_o(t), x_3 = \dot{x}_2(t), x_4 = \dot{x}_o(t) \tag{3.6}$$

The system state space equation can be express as:

$$\frac{dX}{dt} = AX + BU \tag{3.7}$$

In this equation, state variable matrixes are:

$$X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T \tag{3.8}$$

Constant matrixes A and B are shown as below:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1+k_2}{m_2} & \frac{k_1}{m_2} & -\frac{D}{m_2} & \frac{D}{m_2} \\ \frac{k_1}{m_1} & -\frac{k_1}{m_1} & \frac{D}{m_1} & -\frac{D}{m_1} \end{bmatrix} \tag{3.9}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{k_2}{m_2} & \frac{1}{m_2} \\ 0 & -\frac{1}{m_1} \end{bmatrix} \tag{3.10}$$

The system input variable matrix is:

$$U = [x_i(t) \quad u]^T \tag{3.11}$$

The vehicle suspension system output matrix equation is:

$$Y = CX + DU \tag{3.12}$$

In above equation, the output variable matrix Y is:

$$Y = \left\{k_2\left[x_i(t) - x_2(t)\right] \quad \ddot{x}_o(t) \quad x_o(t)\right\} \tag{3.13}$$

Y can also express as the following equation:

$$Y = \left\{k_2\left[x_i(t) - x_1\right] \quad \ddot{x}_2 \quad x_2\right\} \tag{3.14}$$

Constant matrixes C and D are shown as below:

$$C = \begin{bmatrix} -k_2 & 0 & 0 & 0 \\ \frac{k_1}{m_1} & -\frac{k_1}{m_1} & \frac{D}{m_1} & -\frac{D}{m_1} \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3.15}$$

$$D = \begin{bmatrix} k_2 & 0 \\ 0 & -\frac{1}{m_1} \\ 0 & 0 \end{bmatrix} \tag{3.16}$$

The above equations are state space formulas, and we can use Matlab/Simulink State-Space function module, the module is shown as below:

As same as the test we have done in the part of Vehicle Passive Suspension System Mathematical Model Establishment, we still use step signal to test our system, the Simulink structure form is as below:

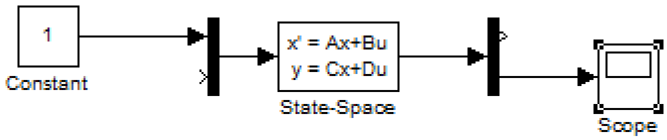


Figure 6 – State space description Simulink model

In this test, we do not add U matrix, so it is a passive suspension system, which is as same as the system built in chapter 3.1, we can see the result in Figure 7 which is as same as Figure 4, but by using different method.

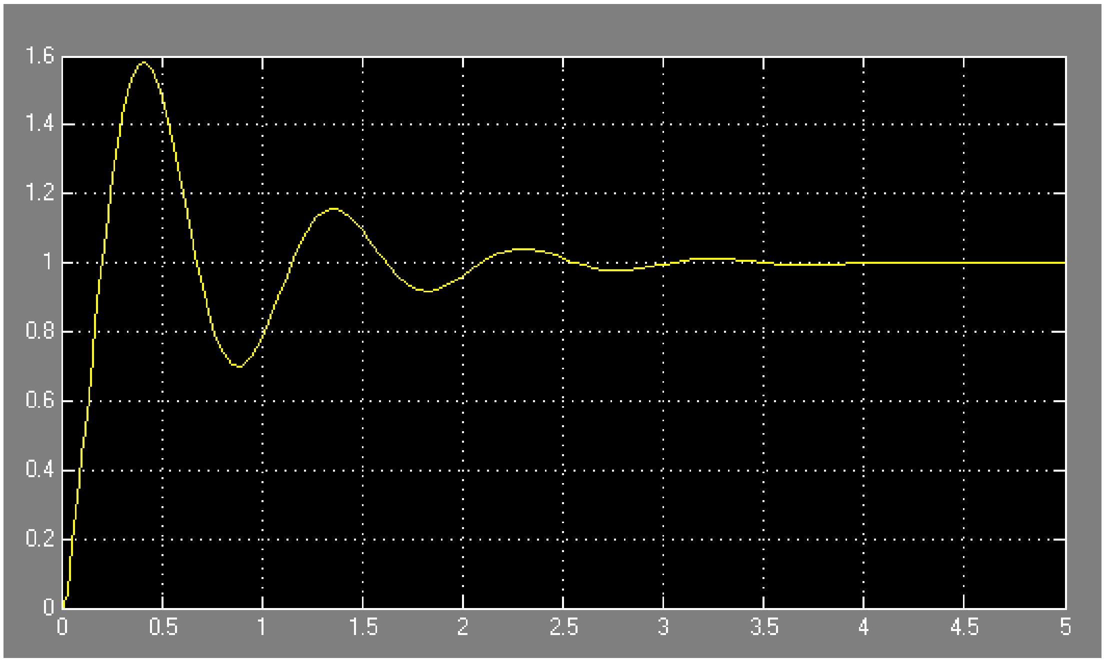


Figure 7 – Passive time domain unit step signal response by using state space description

3.3 Road Input Signals

In this thesis, three types of road input signal will be used to simulate different kinds of road condition. They are step input signal, sine input signal and white noise road input signal. These inputs are the prerequisite to simulate the vehicle suspension system, and they should be accurately reflecting the real road condition when a vehicle drives on the road. Precise signal is crucial to the result of the simulation. We assume the vehicle is a linear system [14].

3.3.1 Step input signal

Step input signal is a basic input to research the suspension system. It simulated a very intense force for a very short time, such as a vehicle drive through a speed hump.

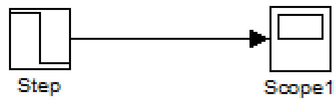


Figure 8 – Unit step signal Simulink model

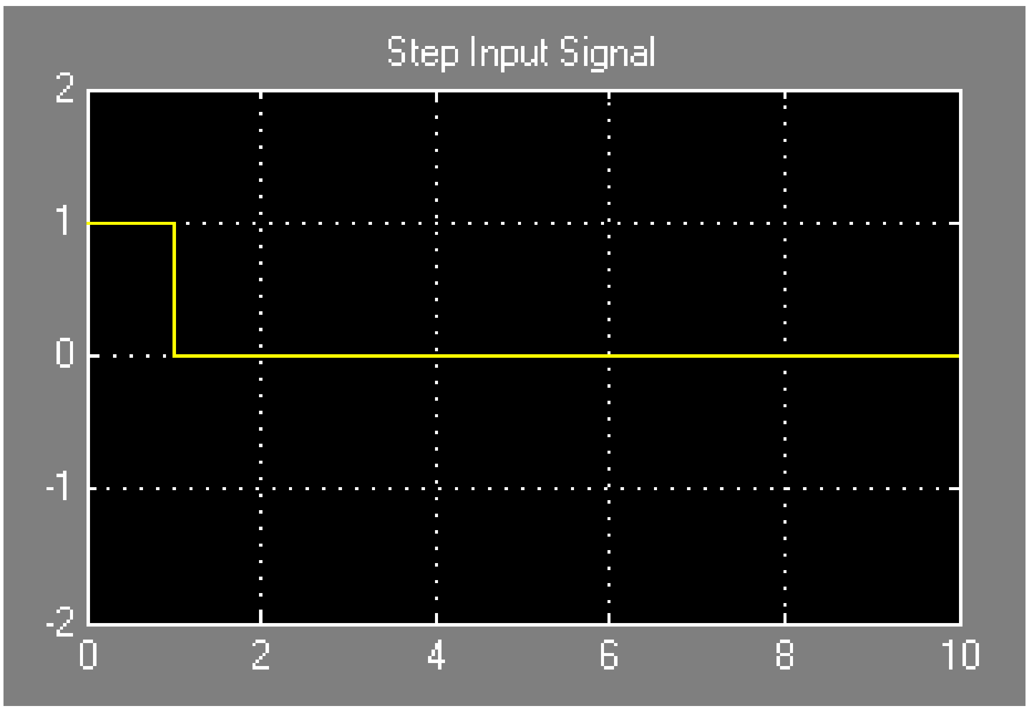


Figure 9 – Unit step input signal

3.3.2 Sine input signal

Sine wave input signal can be used to simulate periodic pavement fluctuations. It can test the vehicle suspension system elastic resilience ability while the car experiences a periodic wave pavement. Sine input pavement test is made by every automotive industries before a new vehicle drives on road [15].

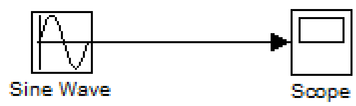


Figure 10 – Sine wave signal Simulink model

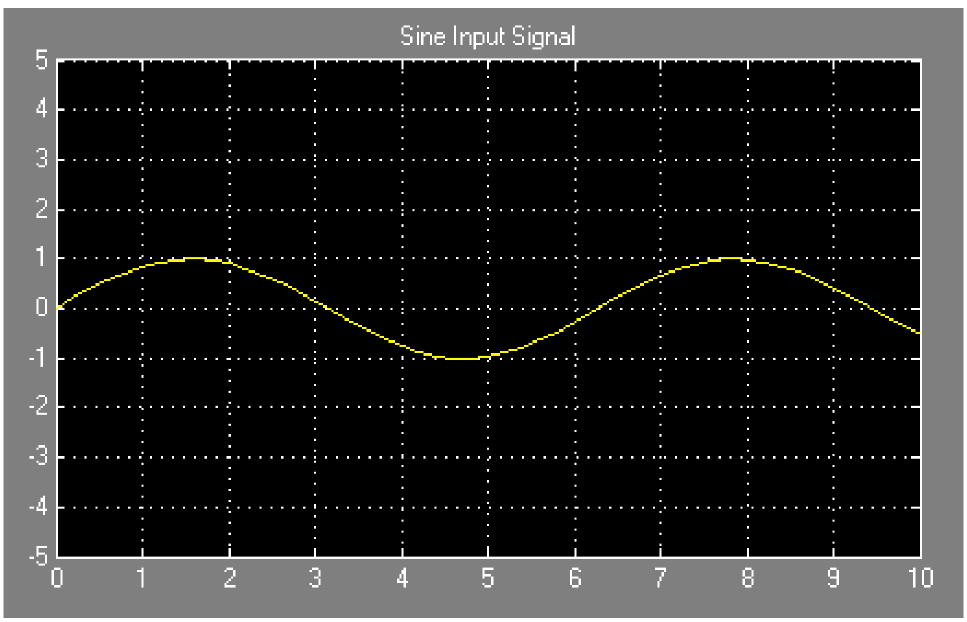


Figure 11 – Unit step input signal

3.3.3 White noise road input signal

Numerous researches show that when the vehicle speed is constant, the road roughness is a stochastic process which is subjected to Gauss distribution, and it cannot be described accurately by mathematical relations. The vehicle speed power spectral density is a constant, which correspond with the definition and statistical characteristic of the white noise, so it can be simply transformed to the road roughness time domain model.

An example for the creation of white noise by using Matlab/ Simulink is shown as below: (noise power is 0.1, sample time is 0.1)

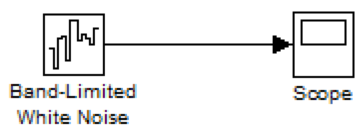


Figure 12 – White noise signal Simulink model

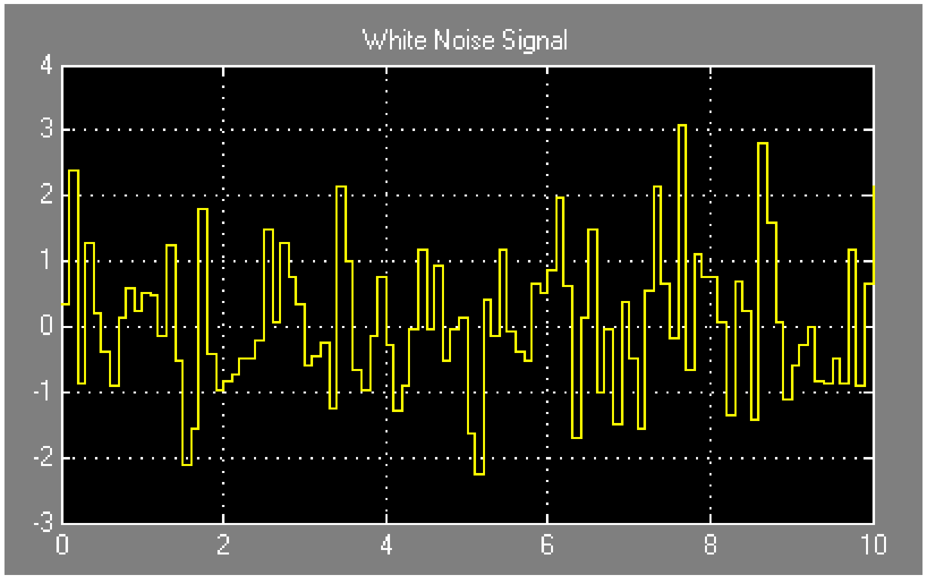


Figure 13 – White noise input signal

The transformation of white noise road input signal can perfectly simulate the actual pavement condition. It has random character when it is used for the vehicle vibration input of road roughness, which is always use the road power spectral density to describe its statistical properties.

According to the ISO/TC108/SC2N67 international standard, it is recommended that the road surface vertical displacement power spectral density (PSD), $G_q(n)$, defined as the following formula as a fitting expression:

$$G_q(n) = G_q(n_0)(\frac{n}{n_0})^{-W} \tag{3.17}$$

n --- Spatial frequency, the reciprocal of the wavelength, unit m^{-1};

n_0 --- Reference Spatial frequency, $n_0=0.1m^{-1}$;

$G_q(n_0)$ --- Road roughness coefficient, unit m^2/m^{-1};

W --- Frequency index, it determines the road surface frequency spectrum structure, usually take the frequency index W=2.

We need to consider velocity when we input the road signal. According to vehicle velocity v, we can transfer spatial frequency power spectral density $G_q(n)$ to time frequency power spectral density $G_q(f)$. When a vehicle drives through a section of road roughness, which spatial frequency is n (unit m^{-1}), and the vehicle velocity is v (unit is ms^{-1}), the time frequency f (unit s^{-1}) is the product of n and v:

$$f = v \times n \tag{3.18}$$

We can get the math relation of time frequency power spectral density $G_q(f)$ and spatial frequency power spectral density $G_q(n)$, which is:

$$G_q(f) = \frac{1}{v} G_q(n) \tag{3.19}$$

When W = 2, we have:

$$G_q(f) = \frac{1}{v} G_q(n_0)\left(\frac{n}{n_0}\right)^{-2} = G_q(n_0) n_0^{\,2} \frac{v}{f^2} \tag{3.20}$$

So $G_q(f)$ is time frequency power spectral density. As well, we can get derivation of the equation and get the vehicle vertical speed power spectral density:

$$G_{\dot{q}}(f) = (2\pi f)^2 G_q(f) = 4\pi^2 G_q(n_0) n_0^2 v \tag{3.21}$$

For steady Gaussian distribution stochastic process, there are many ways to generate road elevation time domain model, such as filtering white noise generation method, random sequence generation method, filtering superposition method, AR (ARMA) method and fast Fourier inverse transform generation method (IFFT). In this thesis, I choose filtering white noise generation method among them, because it has clear physical meaning, easy computing character. So we have [16] :

$$\dot{q}(t) = -2\pi f_0 q(t) + 2\pi n_0 \sqrt{G_q(n_0) v} \cdot w(t) \tag{3.22}$$

q(t) --- Random road input signal;

f_0 --- Filter lower-cut-off frequency;

$G_q(n_0)$ --- Road roughness coefficient, unit m^2/m^{-1};

w(t) --- Gaussian white noise.

Through conducting Laplace transformation to the above equation, we have:

$$\frac{q(s)}{w(s)} = \frac{2\pi n_0 \sqrt{G_q(n_0) v}}{s + 2\pi f_0} \tag{3.23}$$

Set f_0=0, then this transfer function become an integrator form. Here is an example, if a vehicle speed is 20m/s, and it is driving on a class C road, which $G_q(n_0)$ is equals to 256e-6, then the road roughness input signal is as follow:

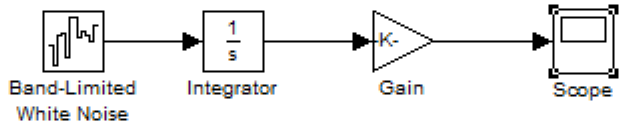


Figure 14 – White noise pavement roughness signal Simulink model

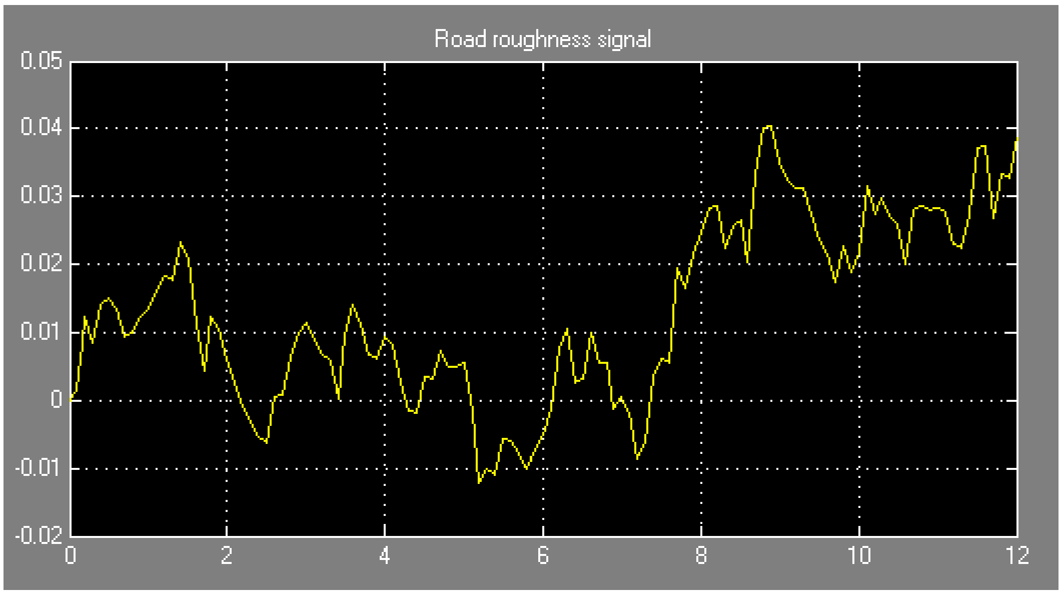


Figure 15 – Class C pavement roughness signal Simulink model

According to the international standard, there are eight road levels, which is from A to H, which A level is the best road level and H is the worst. The following form shows the reference changing with different road level.

The following table 3.3.1 shows different road level's $G_q(n_0)$ and small sigma q geometric average:

Road Level	$G_q(n_0)/(10^{-6}m^3)$ $(n_0 = 0.1m^{-1})$	$\sigma_q/(10^{-3}m)$ $0.011m^{-1} < n < 2.83m^{-1}$
	Geometric Average	Geometric Average
A	16	3.81
B	64	7.61
C	256	15.23
D	1024	30.45
E	4096	60.90
F	16384	121.80
G	65536	243.61
H	262144	487.22

Table 3 - Eight degree of road roughness

In this thesis, we mainly use class C road as our road surface. Through our math model, we can easy change road class by changing parameters used in the simulation.

3.4 Suspension Performance Evaluation Standard

We have already established suspension systems mathematical model and in the next chapter 4 we will discuss the control methods. Here comes a question, how could we judge a better control method and a better suspension type? We need to establish a suspension performance evaluation standard. This standard should be based on objective facts and subjective assessment [17].

There are lots of aspects that vibration affects people, such as acceleration, amplitude, frequency and action directions. Among them, the top reasons that vibration causes people uncomfortable is acceleration and amplitude. So in this thesis, two evaluation standard has been chose: the vehicle body vertical displacement and acceleration, which is $x_o(t)$ and ao(t). We will compare different suspension type with different control methods by outputting their vehicle body vertical displacement and acceleration. The lower $x_o(t)$ and ao(t) means the better performance.

CHAPTER 4 ACTIVE SUSPENSION CONTROL THEORY

4.1 PID Suspension Control System

PID control is by far the most common and practical way in control methods. Since the PID (Proportional Integral Derivative) control method proposed in the early 1940s, the development of this control method has relatively improved. Most of the feedback loop can be used the method or smaller deformation to be controlled. PID regulator and its improved version is the most common controller in industrial process control. Especially for most of the industrial process, precise mathematical model is difficult to establish, so in the process of system analysis and design, the design parameters of the corresponding controller must leave large room for the final determination of the controller parameters, which must rely on the designers based on their experiences in the field setting, therefore, PID controller because of its flexible structure set, parameter tuning, touch-type error robustness, etc. are widely used in industrial practice.

Digital PID algorithm implemented by the computer, due to the flexibility of the software system, the PID algorithm has been further revised and improved. In industrial process control, although automatic control theory and the rapid technological development, especially the development of modern control theory and computer technology, contributed greatly to the industrial automation process, but the PID control technology is still a dominant position, the current control PID type accounts for 84.5%, and optimization of the PID type occupies 6.8%.

Conventional PID control principle framework shown in Figure 16, the system consists of the PID controller and the controlled object.

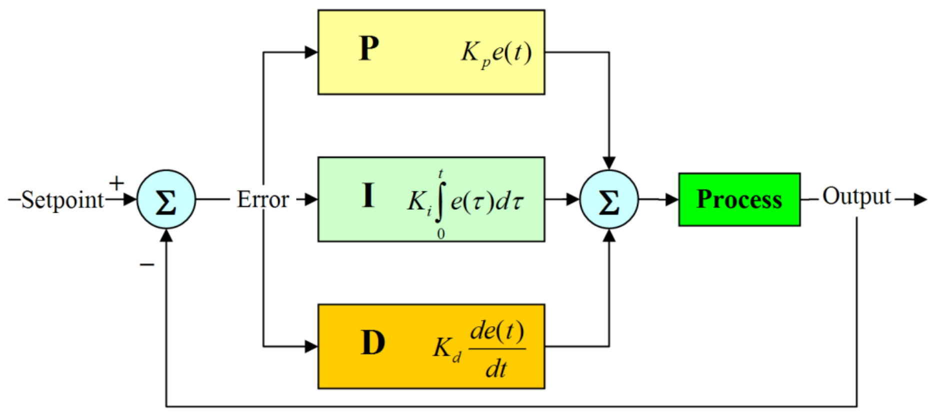


Figure 16 - Typical case PID control chart

The PID controller is a linear controller, which according to the given value r(t) and the actual value c(t) to create of the control deviation [18]:

$$e(t) = r(t) - c(t) \tag{4.1}$$

The amount of deviation constitute with the proportional (P), integral (I) and differential (D) linear combination, to control the control object, so it is called a PID controller.

In continuous-time analog controller, proportion, integral and differential movement's characteristics can be express by the following formula:

$$u(t) = K\left[e(t) + \frac{1}{T_I}\int e(t)dt + T_D\frac{de(t)}{dt}\right] \tag{4.2}$$

In this formula: u(t) is the output of the controller;

K is controller proportional gain;

e(t) is control error, which is the input of controller;

T_I is controller integral time;

T_D is controller differential time.

In computer PID control, the computer can only handle discrete signal, hence we need to transfer PID control algorithm into a discrete form which the computer can be achieved, the discretization of the difference method form as follows:

$$u(k) = k\left\{e(k) + \frac{T}{T_i}\sum_{j=0}^{k}e(j) + \frac{T_d}{T}\left[e(k) - e(k-1)\right]\right\} \tag{4.3}$$

$$u(k) = k_p e_{(n)} + k_i\sum_{j=0}^{k}e_{(j)} + k_d\left[e(k) - e(k-1)\right] \tag{4.4}$$

In it: K_p=K, which is proportional gain; K_i=kT/T_i, which is integral gain; K_d=kT_d/T, which is differential gain. T is sample time, e(k) is the number k sampling deviation value; k is natural number, which k=0,1,2,3,……

We need to find K_p, K_i and K_d to let the system achieve its best working condition. The three parameters have some rules can be followed, which is shown in the following table. This table gives us a guide to find K_p, K_i and K_d.

Reference	**Rise time**	**Overshoot**	**Settling time**	**Steady state error**
$\mathbf{K_p}$	Decrease	Increase	Small Change	Decrease
$\mathbf{K_i}$	Decrease	Increase	Increase	Eliminate
$\mathbf{K_d}$	Small change	Decrease	Decrease	Small change

Table 4 - The relationship between PID reference and time domain factors

4.2 Pavement Monitoring Method

Pavement monitoring method its main theoretical idea is to collect the road surface changing information before the wheel get through it, so the vehicle ECU has enough time to make right decisions to control the active actuator. It based on the road surface wave signal collection system. We assume that the vehicle installs this system and it continuously collects road surface changing information [19].

For unit step and sine wave signal, the active force can be expressed as the follow equation:

$$u = -lx_i(t) \tag{4.5}$$

From above equation we can see that the active force u is relative to the road input signal $x_i(t)$, l is a proportionality coefficient.

For white noise signal, above equation can be transform to the following equation:

$$u = -l\int_0^{\Delta t} w(t)d\Delta t \tag{4.6}$$

We need to find an appropriate proportionality coefficient l to make the active force reasonable and effective. Delta t is a very small time change, and in the next chapter simulation process, the Delta t is assigned to 0.01s, which is as same as the system sample time. W(t) is the white noise generator.

4.3 New Algorithm Establishment

In chapter 4.3, we will discuss how we could create the active force. There are many methods to generate the active force, such as the famous semi-active control method-sky-hook method and the ground-hook method. In these methods, the active force variable is only decided by the relative speed of m_1 and m_2, which is the relative vertical speed of vehicle body speed and wheel speed. Our new algorithm define u is decided by the relative position of body mass and wheel, and also decided by the body mass movement speed.

After trying several formulas, the following equation is defined as the active force fitting formula:

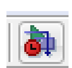
$$u = -\left\{ l_1 \left[x_o(t) - x_2(t) \right] + l_2 \frac{dx_o(t)}{dt} \right\} \tag{4.7}$$

In the above equation, u is the active force created by active actuator; l_1 and l_2 are two proportionality coefficients, which is different in each vehicle model; as same as pavement monitoring method, two appropriate proportionality coefficient l_1 and l_2 must be find to make the active force reasonable and effective. According to the fitting formula, u is sum of two parts; the first part $-l_1*[x_o(t)-x_2(t)]$ can be regarded as an additional spring system, while the second part $-l_2*dx_o(t)/dt$ can be regarded as a damping system. So we can look the active force u as a resultant force of two active devices. The relative position coefficient can be known by using relative displacement transducer, and the output speed can be acquired by velocity sensor. This algorithm is not the one that most effective in my experiments, but it is the most stable, easy control and will not make the system divergence. In the time response analysis in the next chapter, the control system reaction time will not be considered [20].

CHAPTER 5 SIMULATION STRUCTURE AND RESULT

5.1 Simulink Introduction

Simulink, developed by MathWorks, is a data flow graphical programming language tool for modeling, simulating and analyzing multidomain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multidomain simulation and Model-Based Design.

To start Simulink, click  button in the MATLAB.

5.2 Passive Suspension Simulink Structure and Results

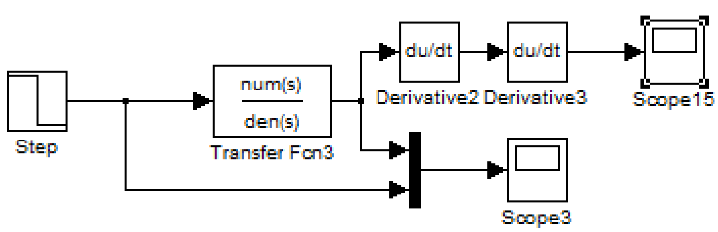


Figure 17 - Passive suspension system Simulink structure with the unit step input

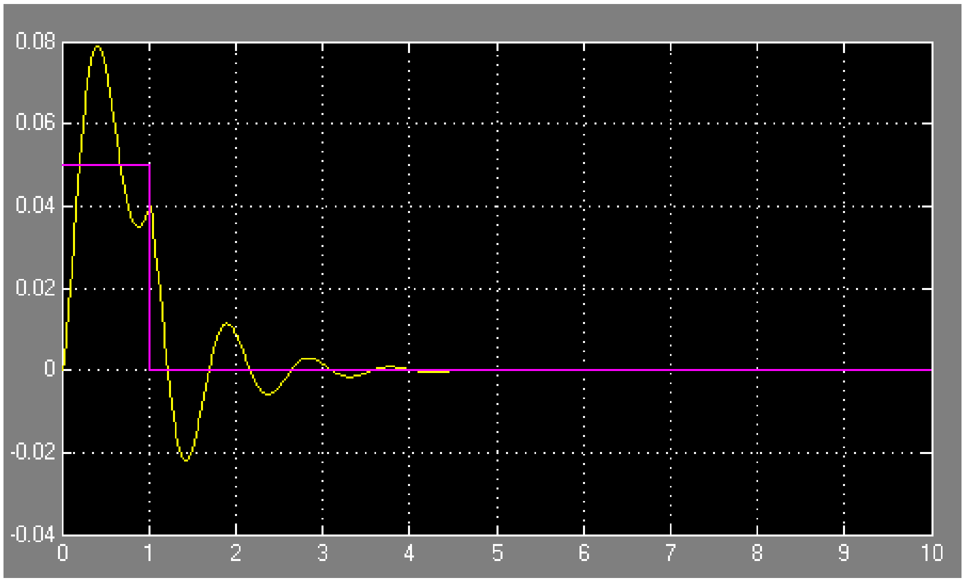


Figure 18 - The Passive suspension system output displacement time response with the input of unit step signal

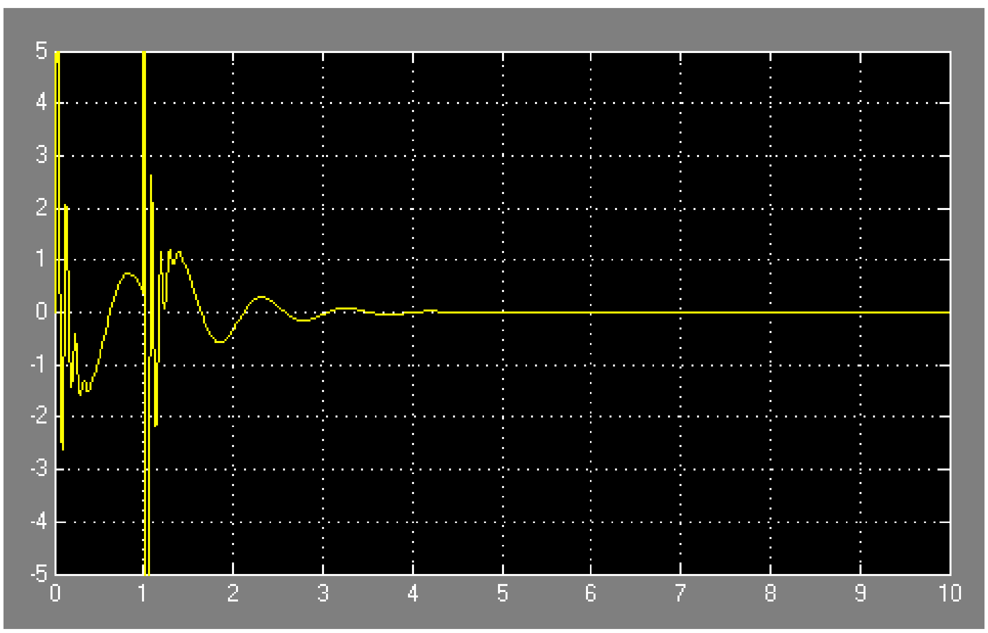


Figure 19 - The Passive suspension system output acceleration time response with the input of unit step signal

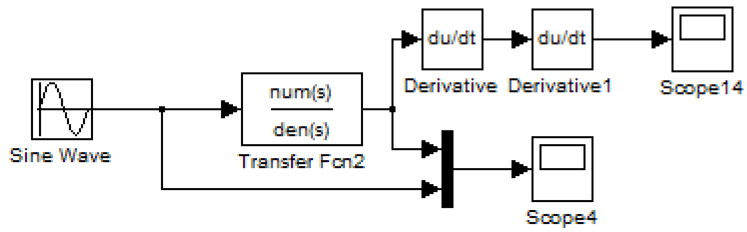


Figure 20 - Passive suspension system Simulink structure with the sine wave input

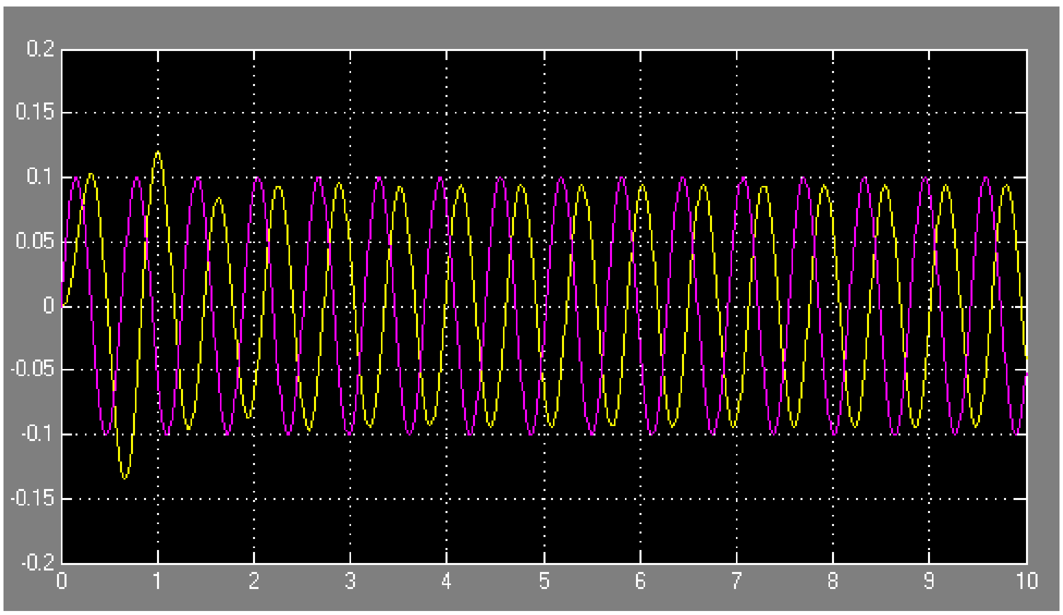


Figure 21 - The passive suspension system output displacement time response with the input of sine wave signal (purple line is sine wave signal)

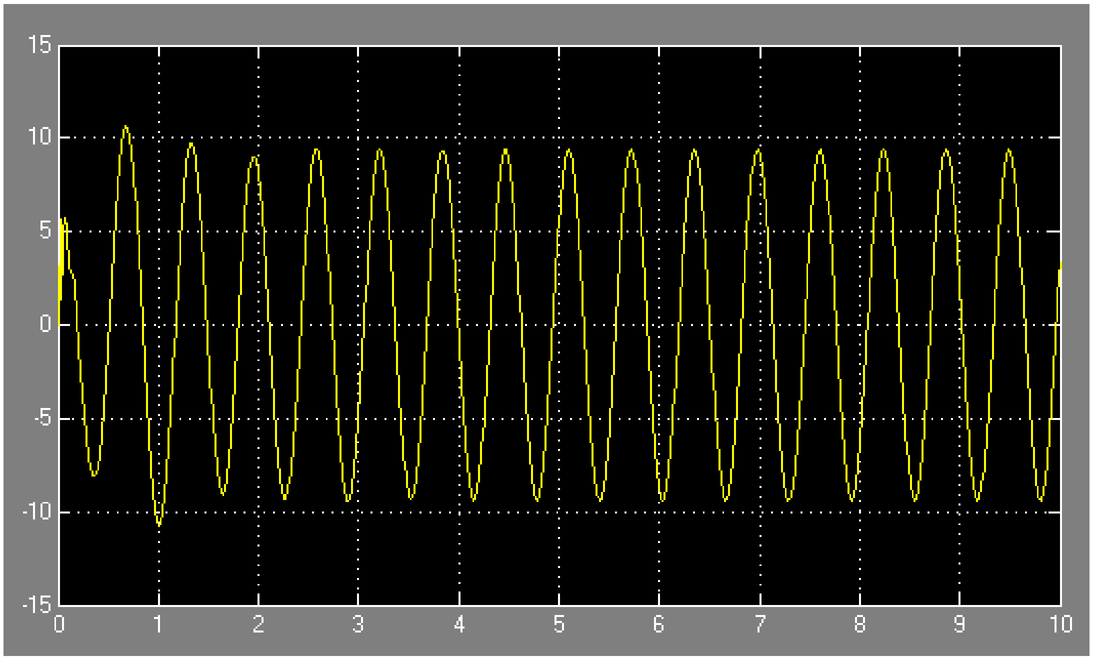


Figure 22 - The Passive suspension system output acceleration time response with the input of sine wave signal

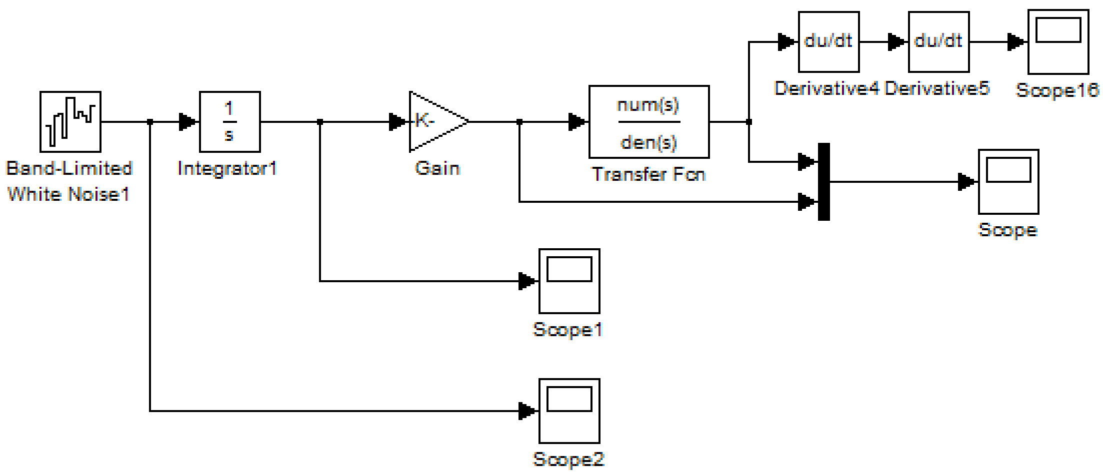


Figure 23 - Passive suspension system with white noise input

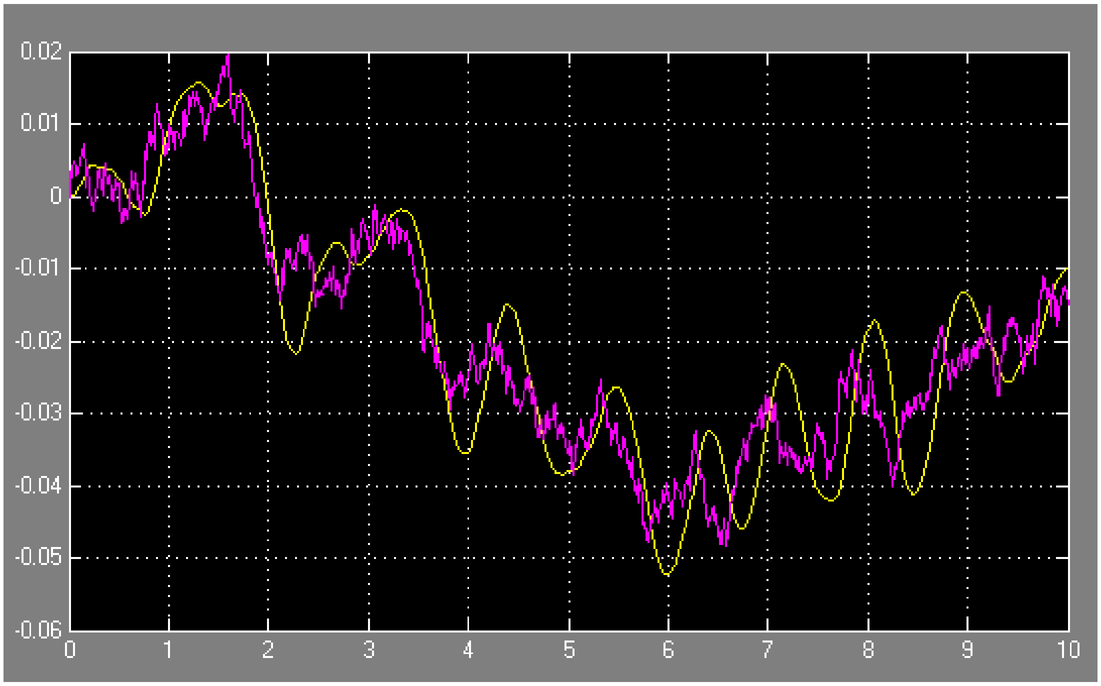


Figure 24 - The passive suspension system output displacement time response with the input of white noise signal (purple line is white noise signal)

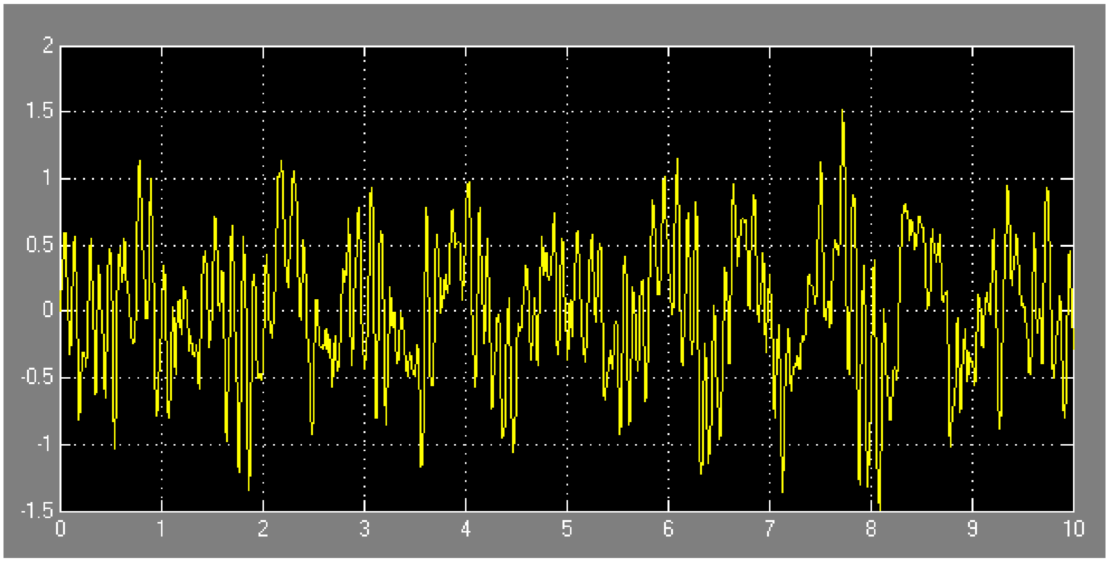


Figure 25 - The Passive Suspension system output acceleration time response with the input of white noise signal

From above pictures, we can see that passive active suspension system cannot reduce vibration. It can only control the vibration to a limit extent. The suspension travel strokes are even larger than the road surface wave amplitude. The accelerations are also cannot get effective reduction.

5.3 PID Active Suspension Simulink Structure and Result

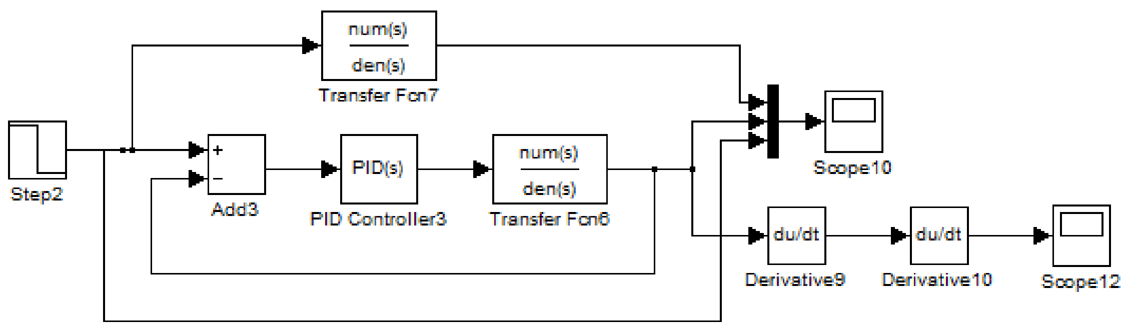


Figure 26 - PID control active suspension system Simulink structure with the unit step input

Figure 26 shows a set of PID control active suspension system Simulink structure with the unit step input. A PID controller is added into the system and the displacement feedback is added with the origin signal. The above transfer function module is passive suspension system, which is the experiment control group. Two signal output is displacement and acceleration.

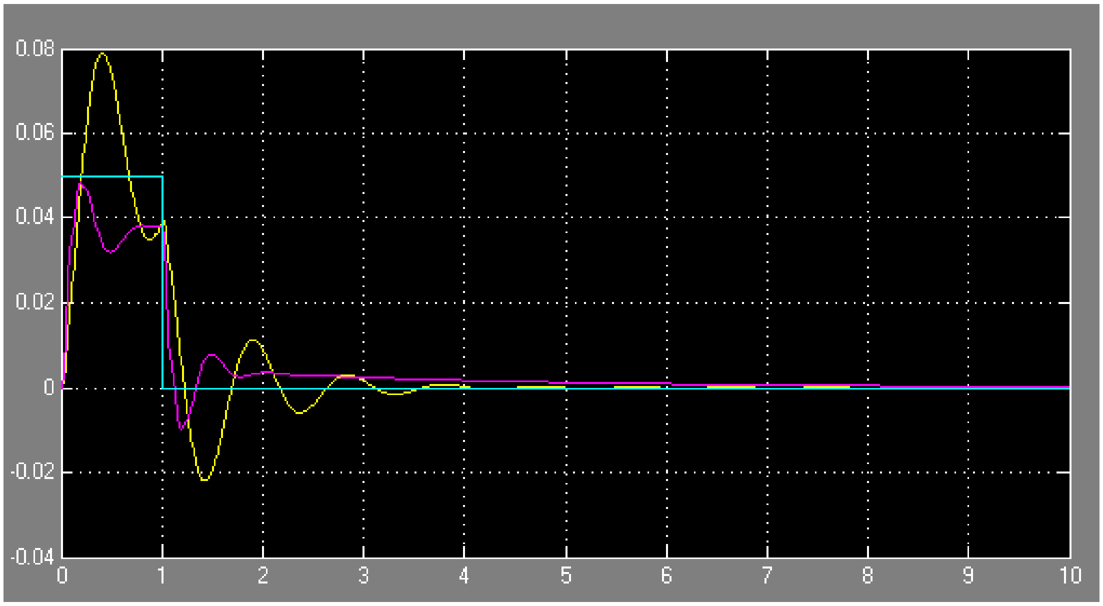


Figure 27 - PID control active suspension system compare with passive suspension system output displacement time response with the input of unit step signal

Figure 27 shows the passive suspension system and PID control active suspension system displacement change over time. The yellow line is passive system, and the purple line is PID control system. We can see that, compare to the passive suspension system, the PID control active suspension system successful reduce the amplitude of the vibration. The PID active suspension system's output displacement amplitude is lower than the unit step signal's amplitude.

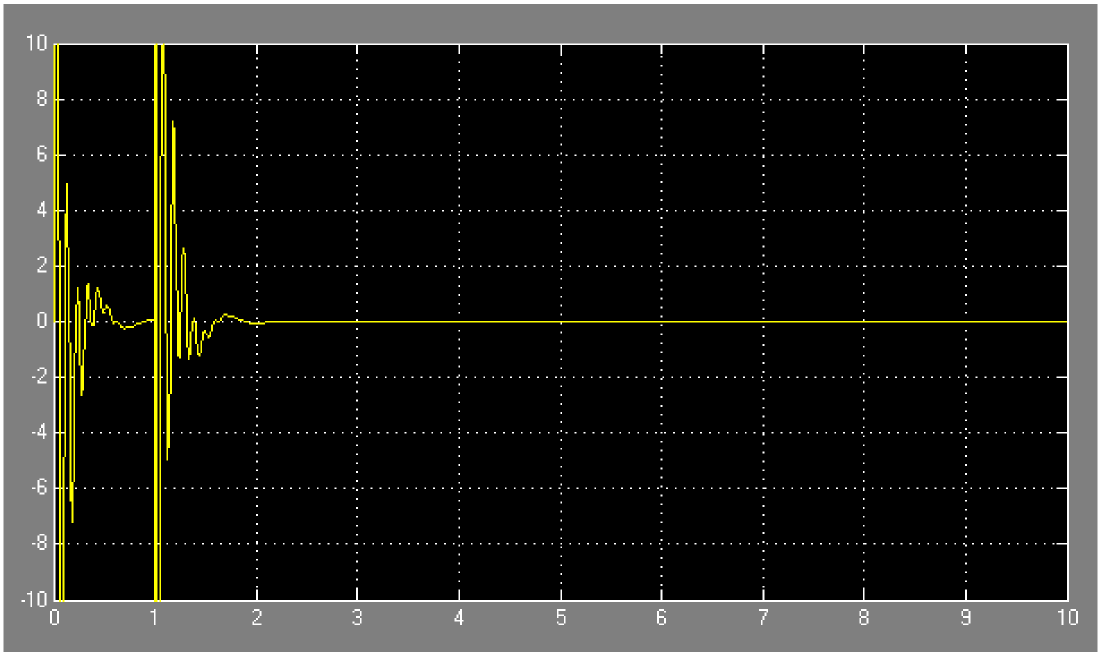


Figure 28 - PID control active suspension system output acceleration time response with the input of unit step signal

Figure 28 shows the PID active system acceleration change over time. Compare it with Figure 19; we can see that the PID active system has not reduced the output acceleration, but increased nearly one time. It indicates that this kind of control system still have some aspects to improve.

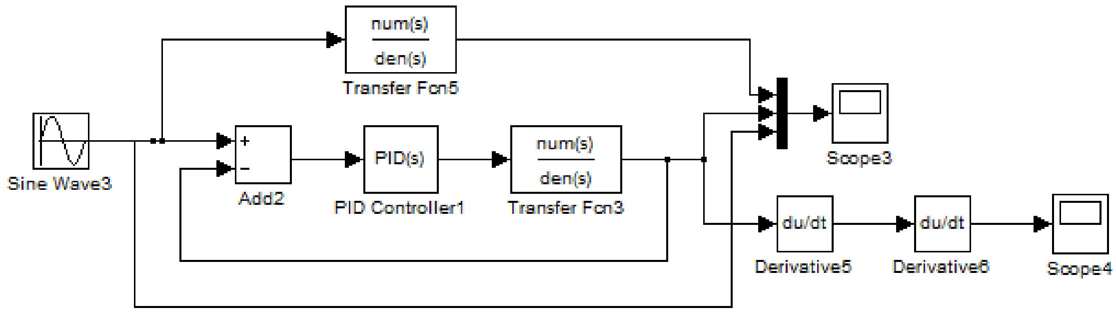


Figure 29 - PID control active suspension system Simulink structure with the sine wave input

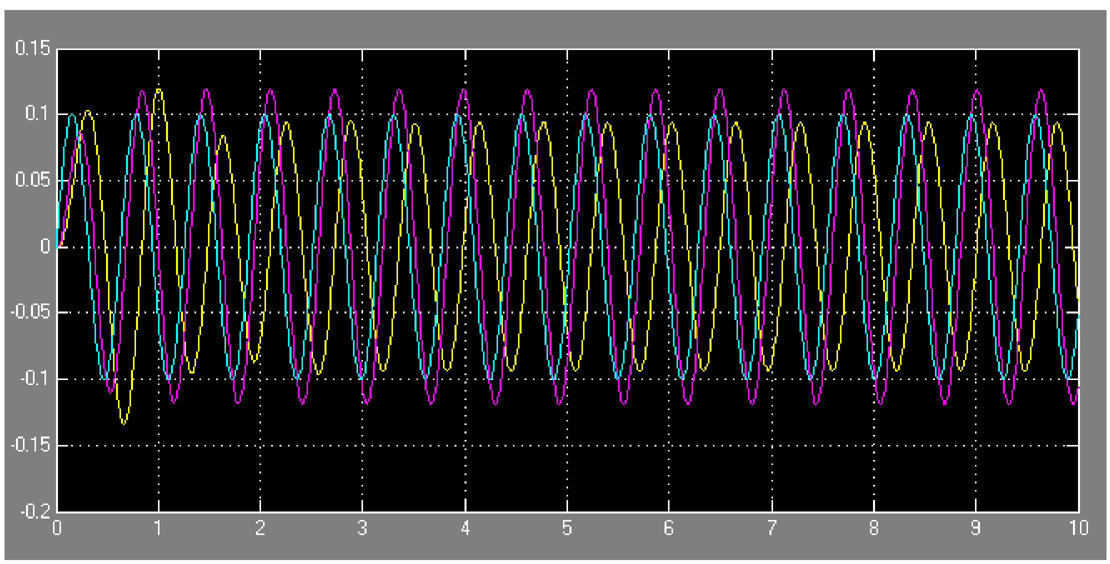


Figure 30 - PID Control Active Suspension System compare with Passive Suspension system output displacement time response with the input of Sine Wave signal

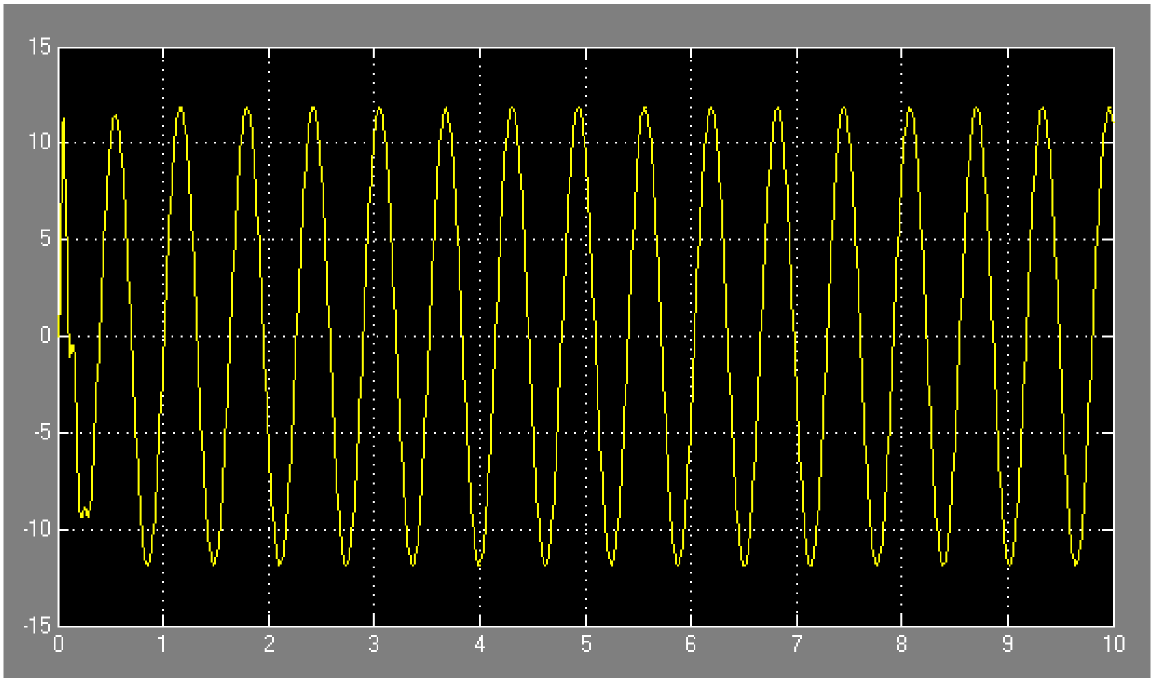


Figure 31 - PID control active suspension system output acceleration time response with the input of sine wave signal

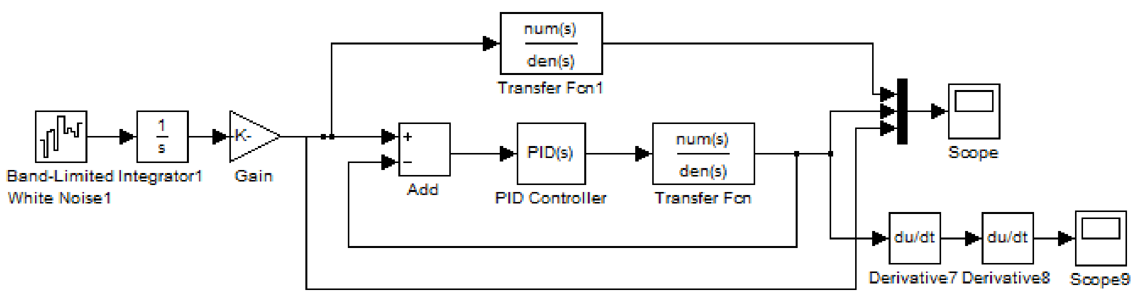


Figure 32 - PID control active suspension system Simulink structure with the white noise input

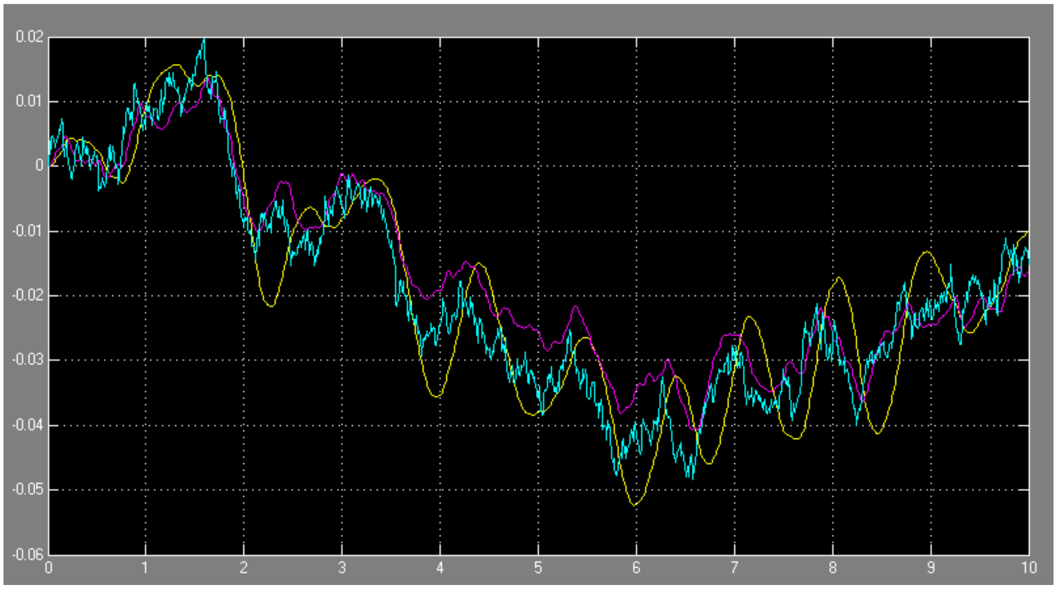


Figure 33 - PID Control Active Suspension System compare with Passive Suspension system output displacement time response with the input of White Noise signal

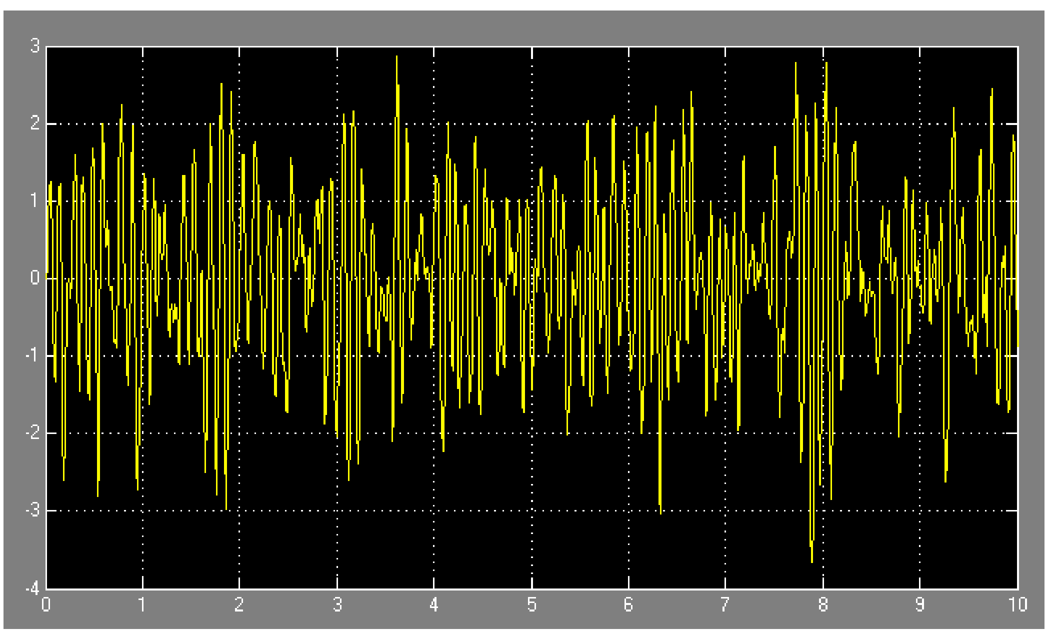


Figure 34 - PID control active suspension system output acceleration time response with the input of white noise signal

Figure 30 - Figure 34 indicates that PID control active suspension system has good effective to reduce output displacement. But it increases the acceleration about one time compare to the passive suspension system.

5.4 Pavement Feedback Active Suspension Simulink Structure and Result

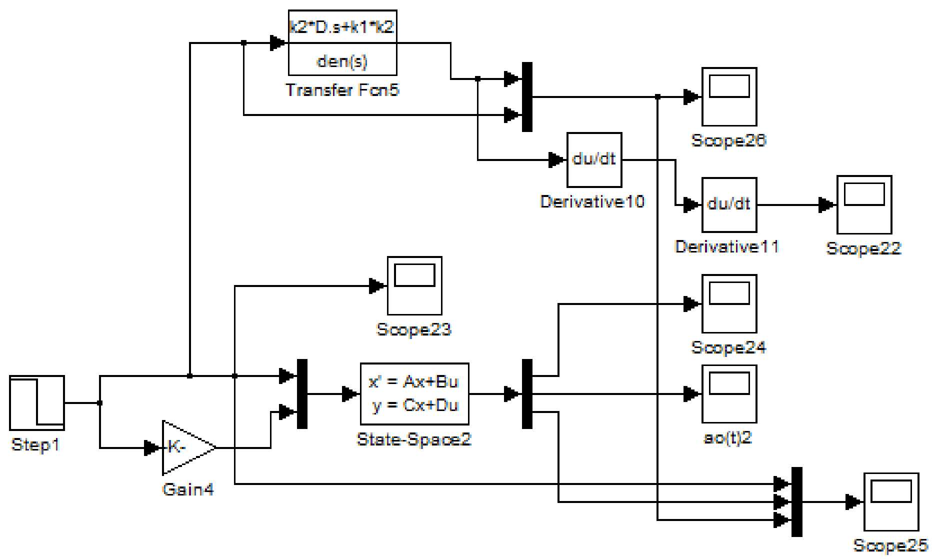


Figure 35 - Pavement feedback active suspension system Simulink structure with the step signal input

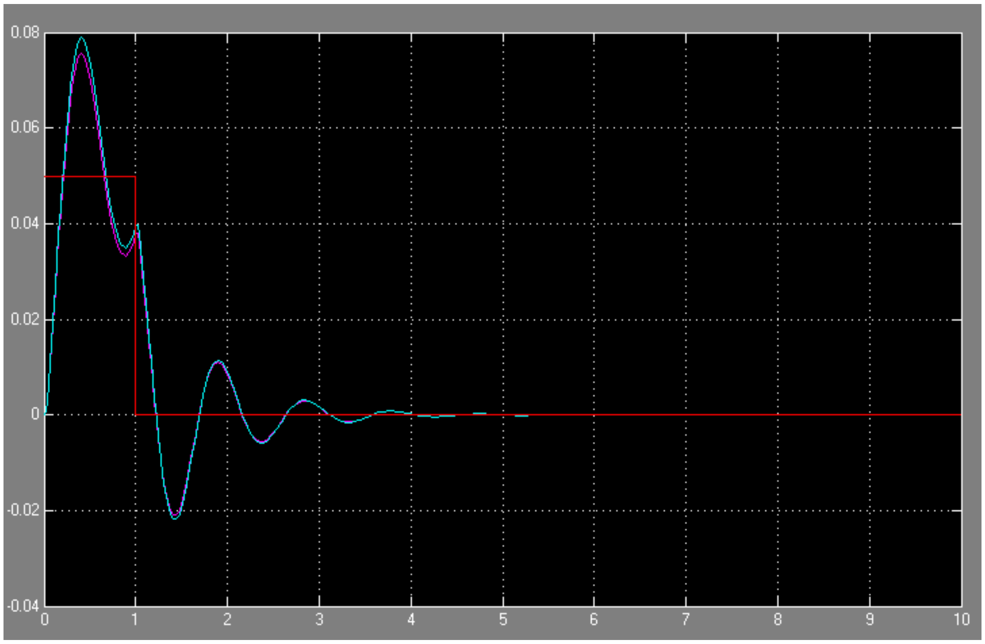


Figure 36 - Pavement feedback active suspension system compare with passive suspension system output displacement time response with the input of unit step signal

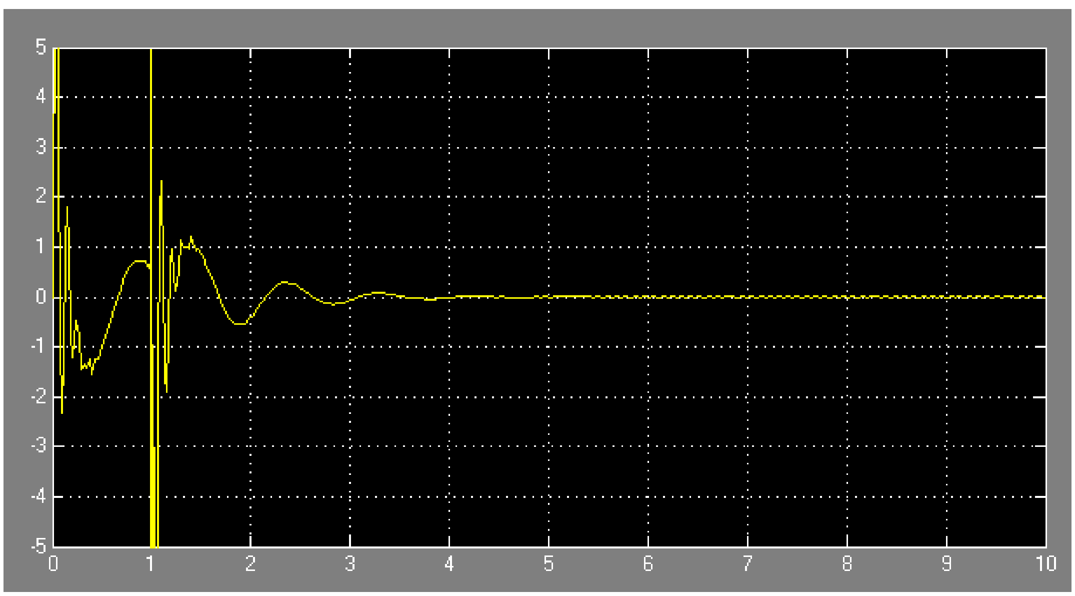


Figure 37 - Pavement feedback active suspension system output acceleration time response with the input of unit step signal

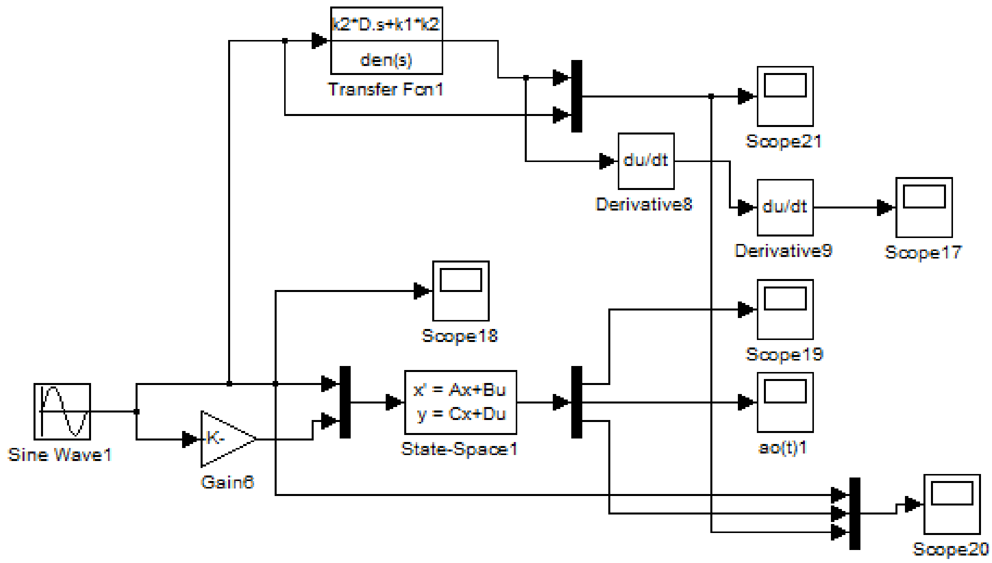


Figure 38 - Pavement feedback active suspension system Simulink structure with the sine wave input

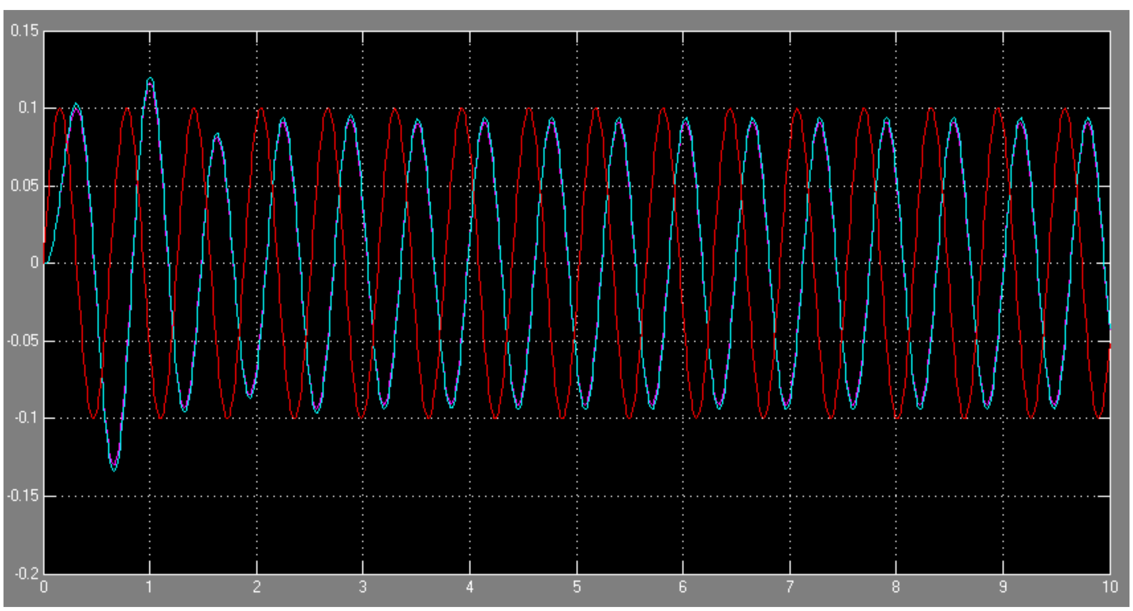


Figure 39 - Pavement feedback active suspension system compare with passive suspension system output displacement time response with the input of sine wave signal

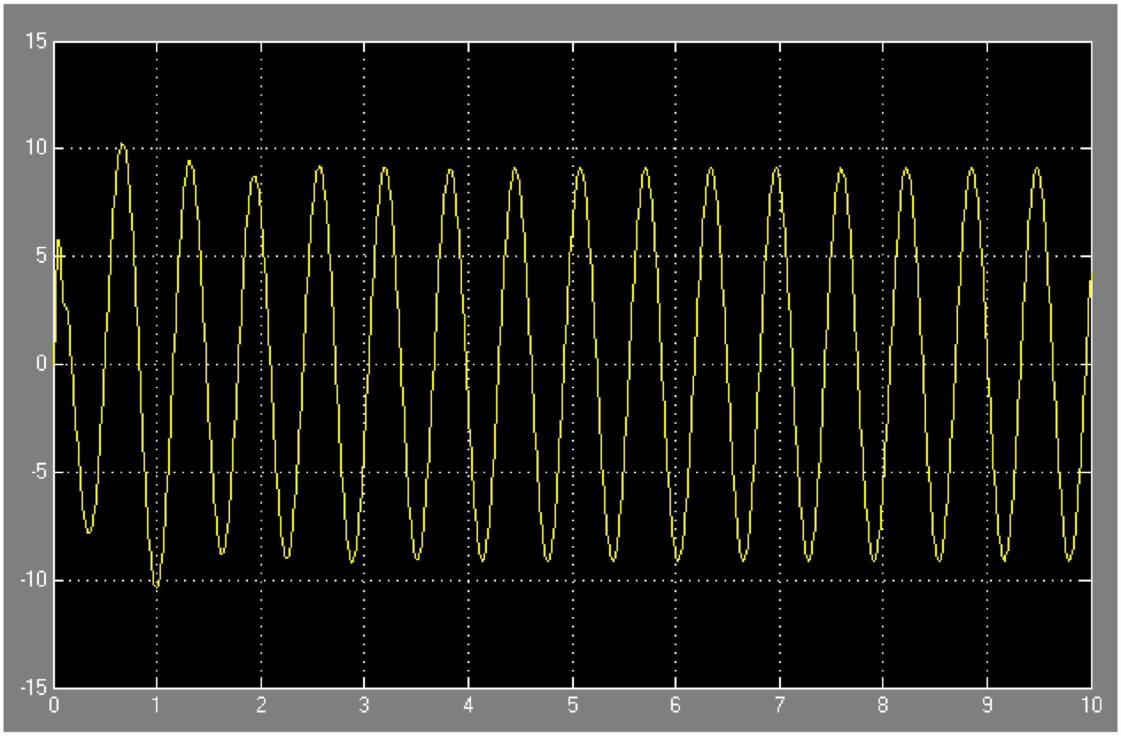


Figure 40 - Pavement feedback active suspension system output acceleration time response with the input of sine wave signal

Figure 36, 37, 39 and 40 shows that the vehicle output displacement and acceleration is reduced about 5%, which can slightly improve the vehicle suspension performance. But this method has great change when use white noise signal shown as following Figures from 41 - 43.

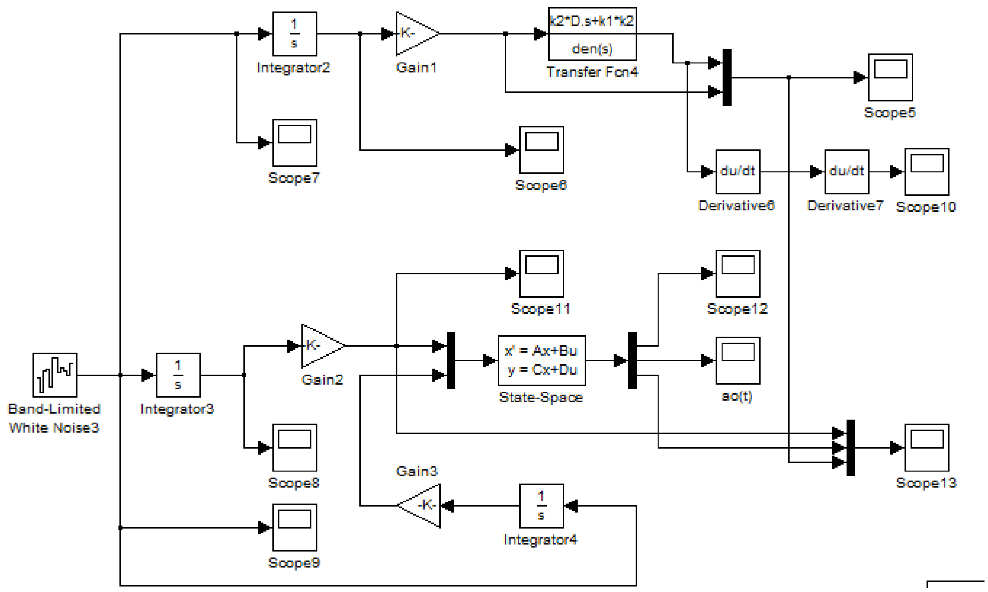


Figure 41 - Pavement feedback active suspension system Simulink structure with the white noise input

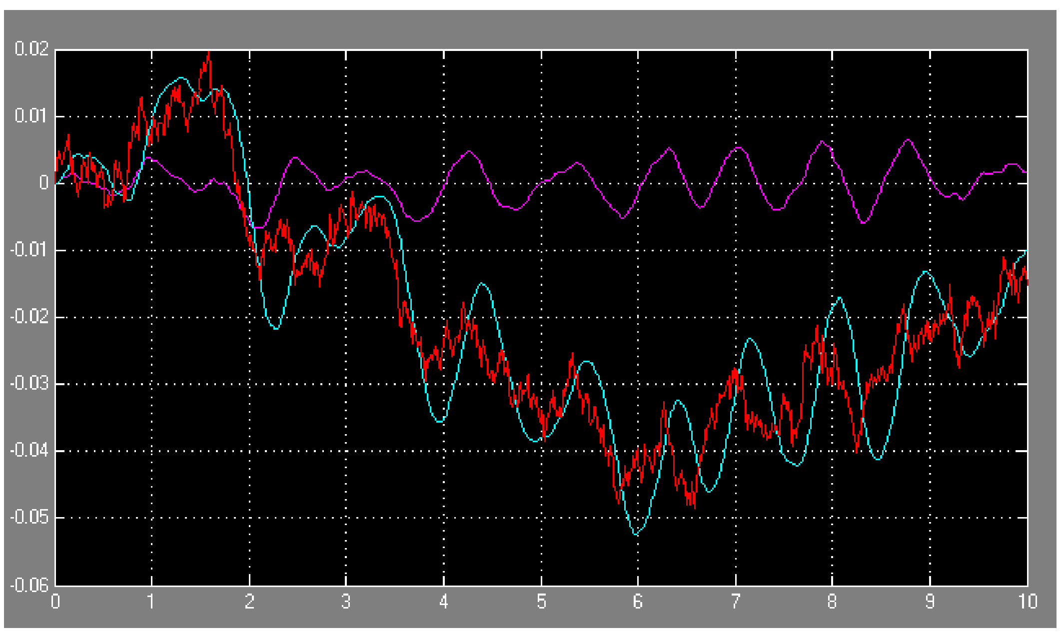


Figure 42 - Pavement feedback active suspension system compare with passive suspension system output displacement time response with the input of white noise signal

From Figure 42, we got a nearly wave steady purple line, which is the pavement feedback active suspension system. It greatly changes the suspension system performance. This line means that the pavement feedback active suspension system can maintain a very low output displacement regardless of the input white signal. It also shows a great reliability and stability.

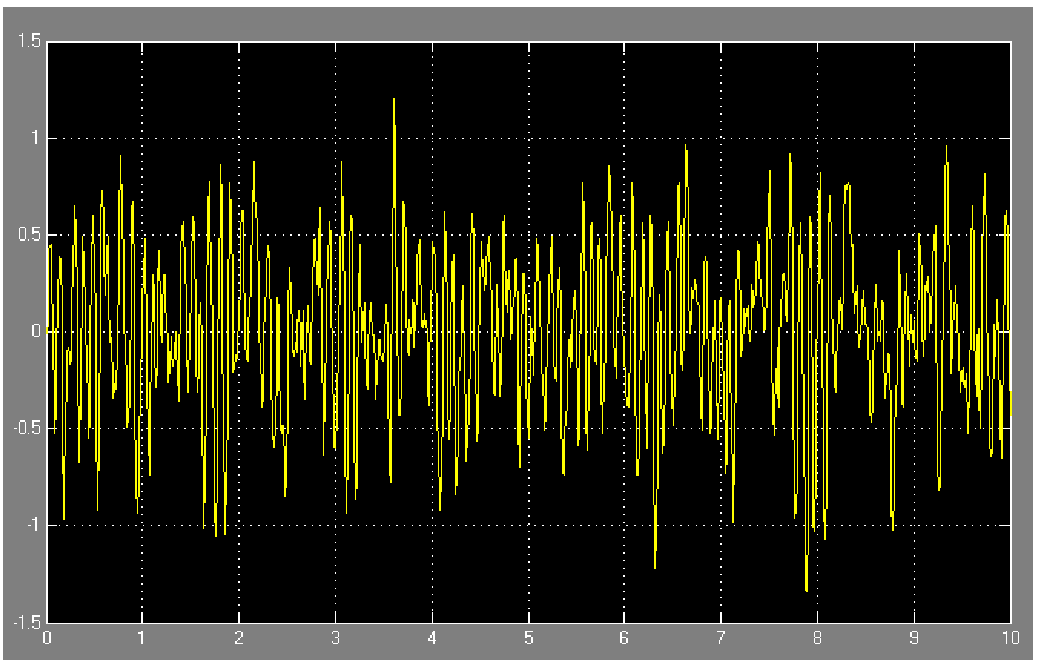


Figure 43 - Pavement feedback active suspension system output acceleration time response with the input of white noise signal

Compare Figure 43 and Figure 25, we can know that the pavement feedback active suspension system output acceleration time response is decreased about 25%, which is also a great change. This kind of control method can not only improve the output displacement, but also the acceleration.

5.5 New Algorithm Active Suspension Simulink Structure and Result

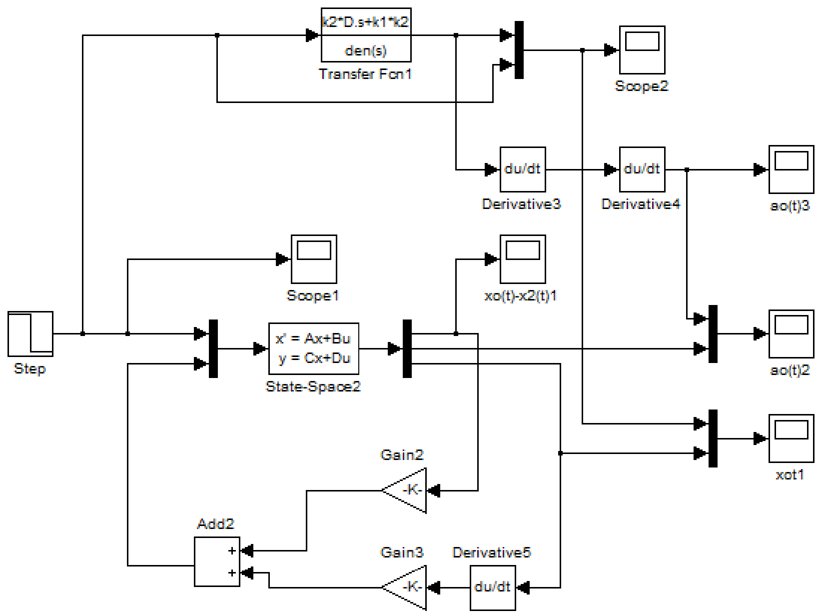


Figure 44 - New algorithm active suspension system Simulink structure with the step signal input

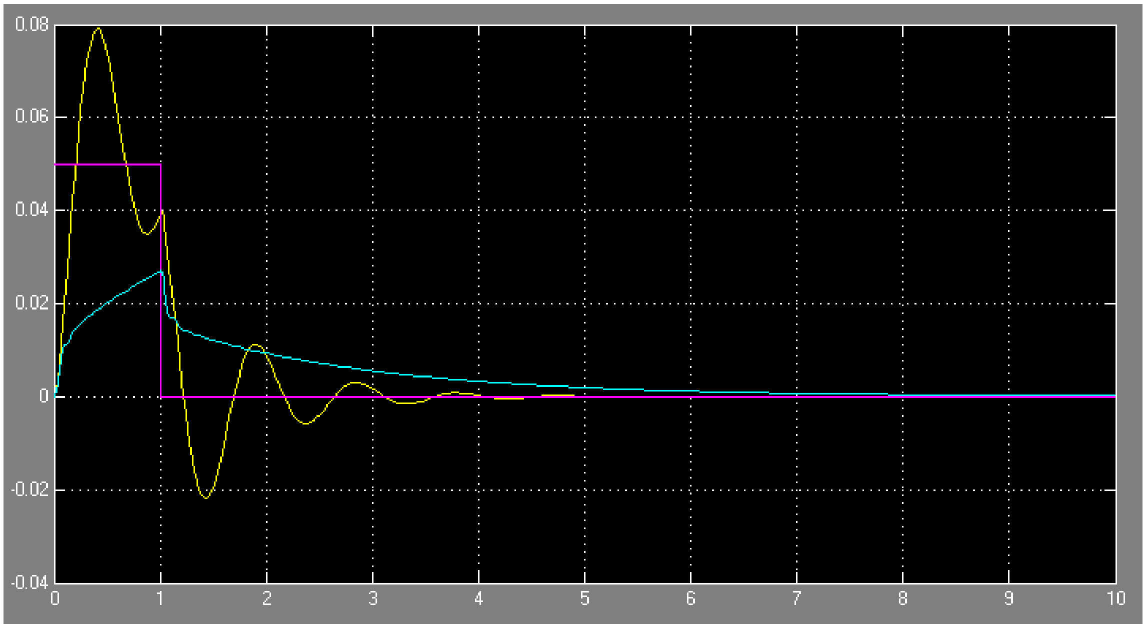


Figure 45 - New algorithm active suspension system compare with passive suspension system output displacement time response with the input of unit step signal

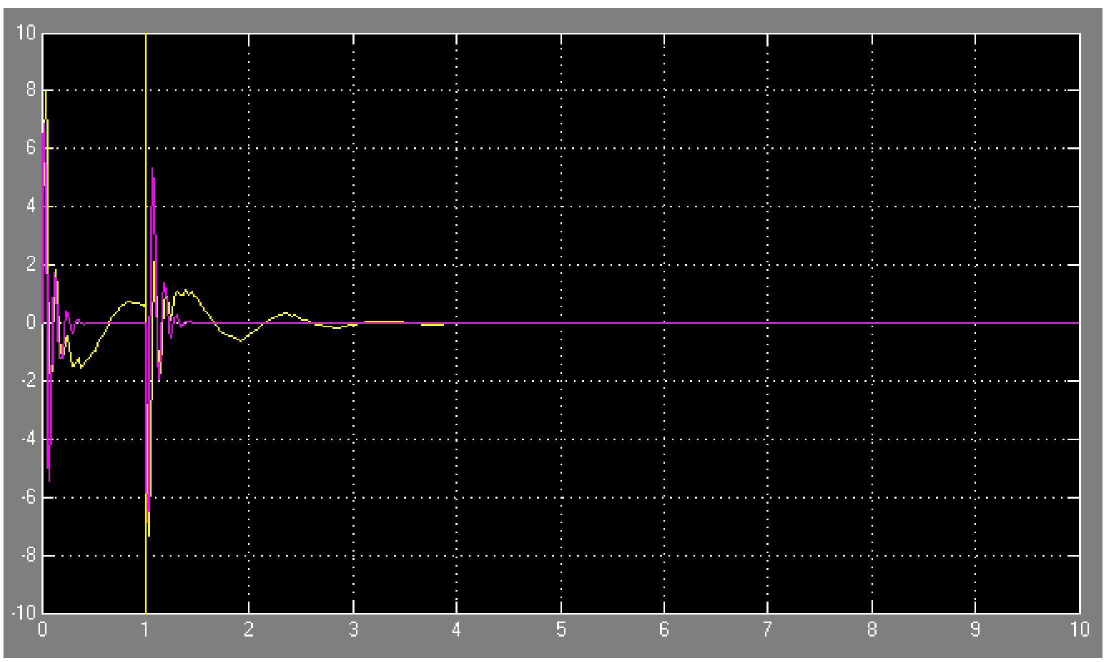


Figure 46 - New algorithm active suspension system output acceleration time response with the input of unit step signal, and compare with passive suspension system

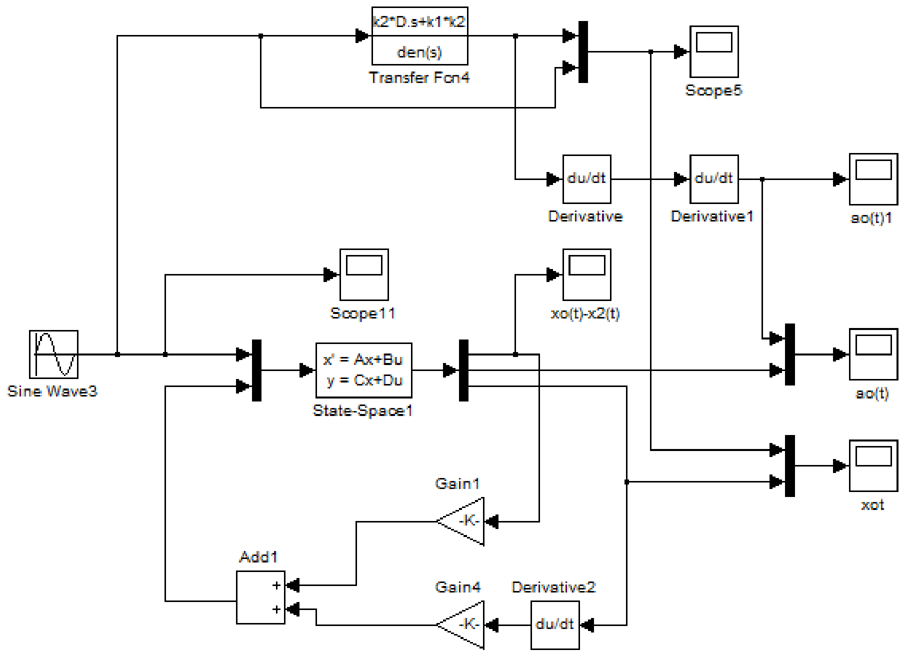


Figure 47 - New algorithm active suspension system Simulink structure with the sine wave input

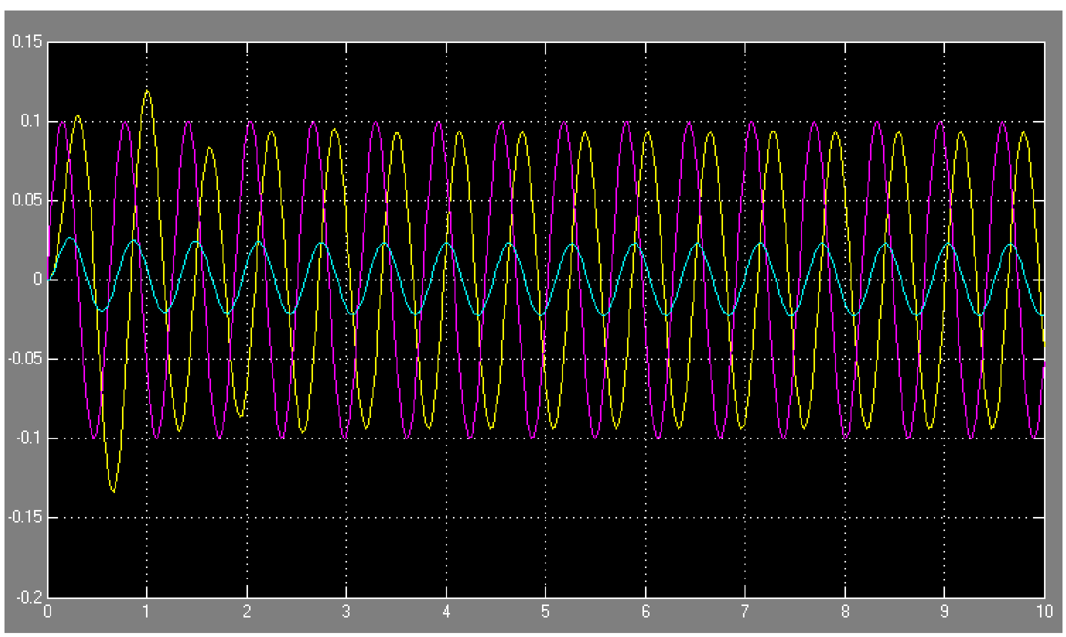


Figure 48- New algorithm active suspension system output acceleration time response with the input of sine wave signal, and compare with passive suspension system

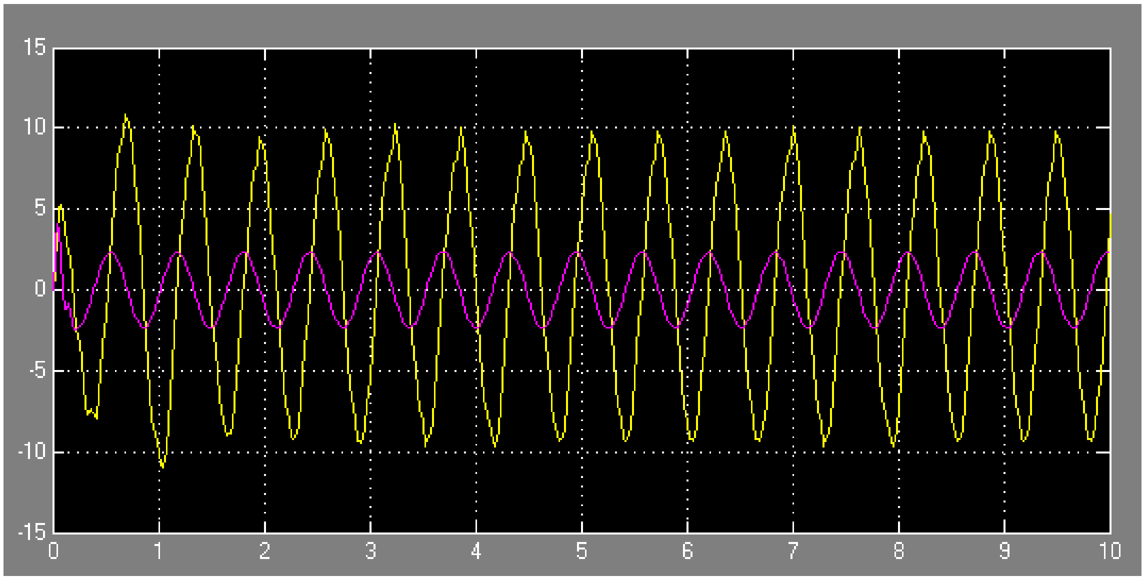


Figure 49 - New algorithm active suspension system output acceleration time response with the input of sine wave signal, and compare with passive suspension system

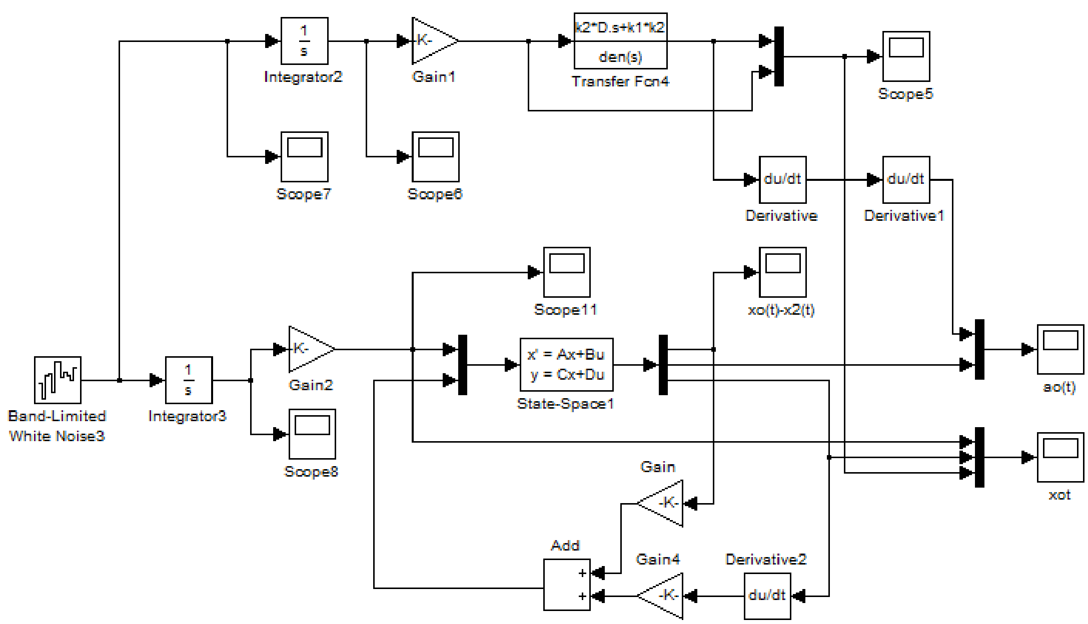


Figure 50 - New algorithm active suspension system Simulink structure with the white noise input

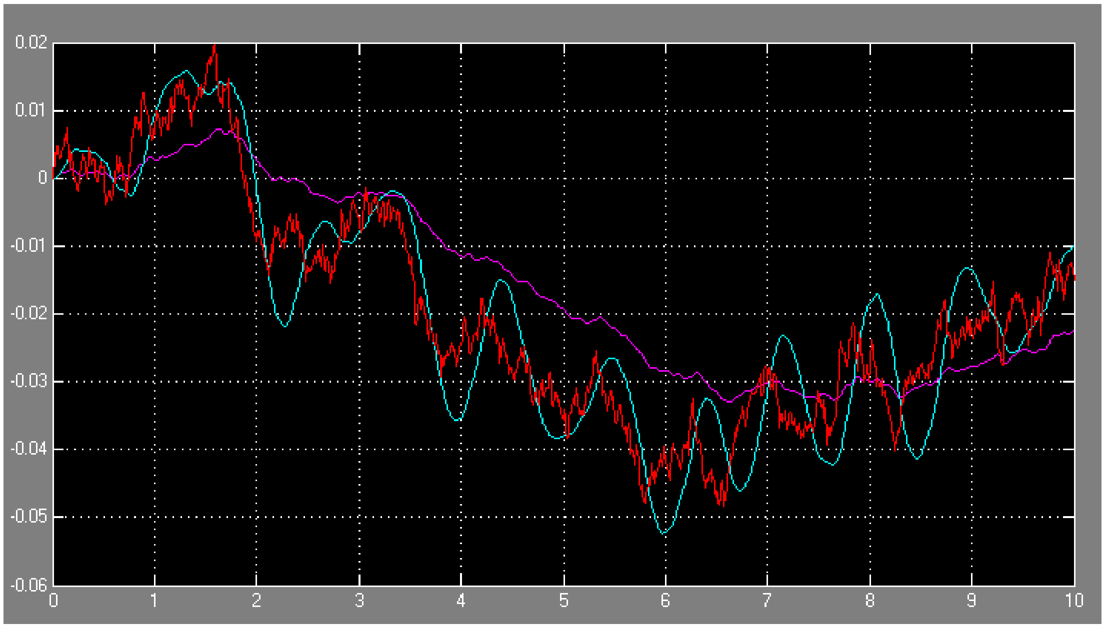


Figure 51 - New algorithm active suspension system compare with passive suspension system output displacement time response with the input of white noise signal

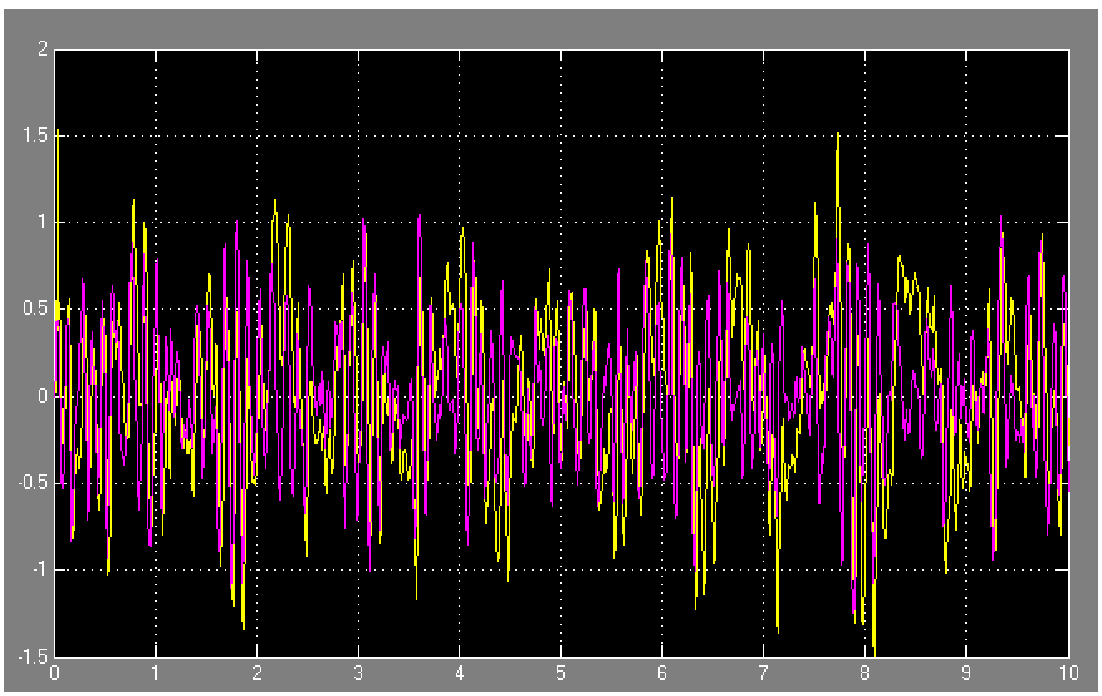


Figure 52 - New algorithm active suspension system output acceleration time response with the input of white noise signal, and compare with passive suspension system

We can see from above figures that new algorithm active suspension control system has great performance, especially the displacement when use the white noise input. The Curves do not appear large fluctuations. For acceleration, new algorithm active suspension control system decreases about 50%. Overall equipment effectiveness is even much better than the pavement feedback system.

5.6 New Algorithm PID control Active Suspension System Simulink Structure and Results

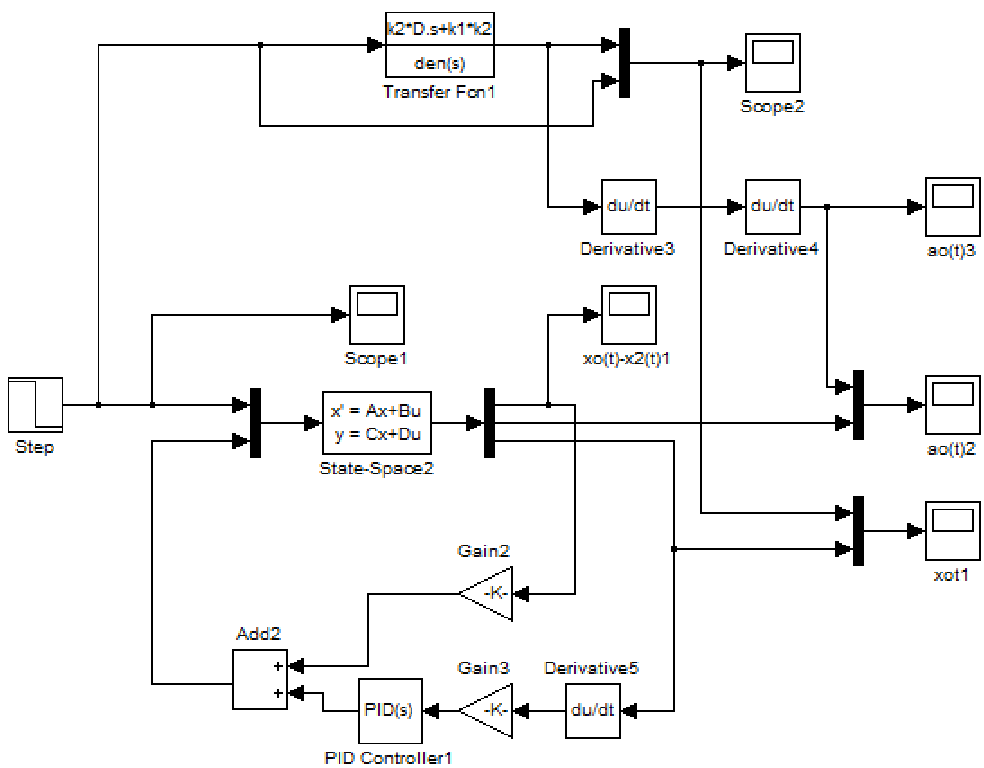


Figure 53 - New algorithm PID control active suspension system Simulink structure with the step signal input

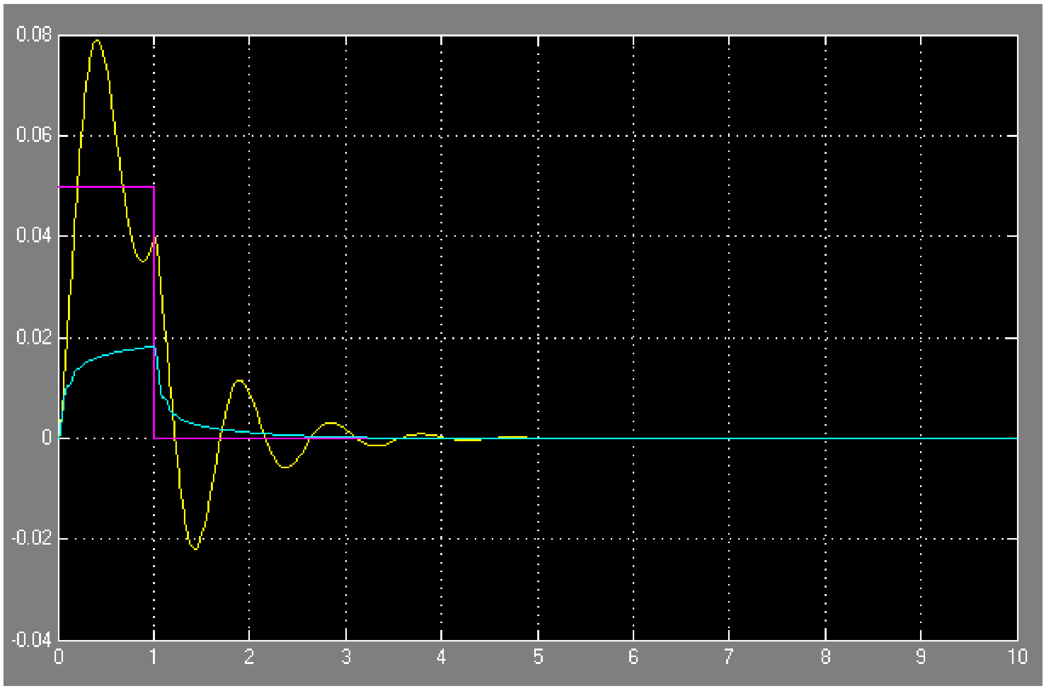


Figure 54- New algorithm PID control active suspension system compare with passive suspension system output displacement time response with the input of unit step signal

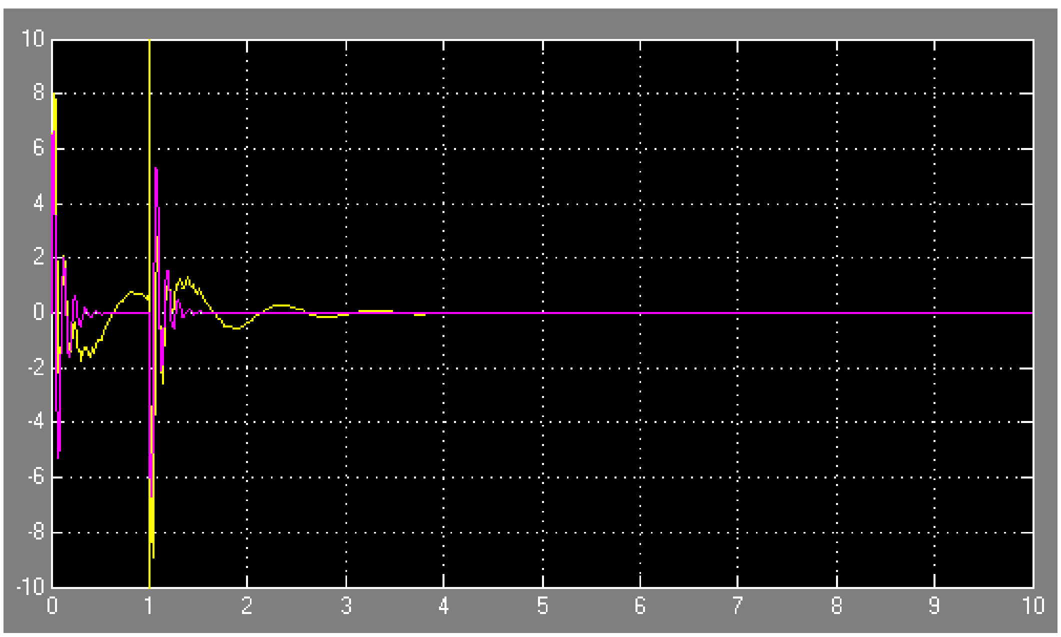


Figure 55 - New algorithm PID control active suspension output acceleration time response with the input of unit step signal, and compare with passive suspension system

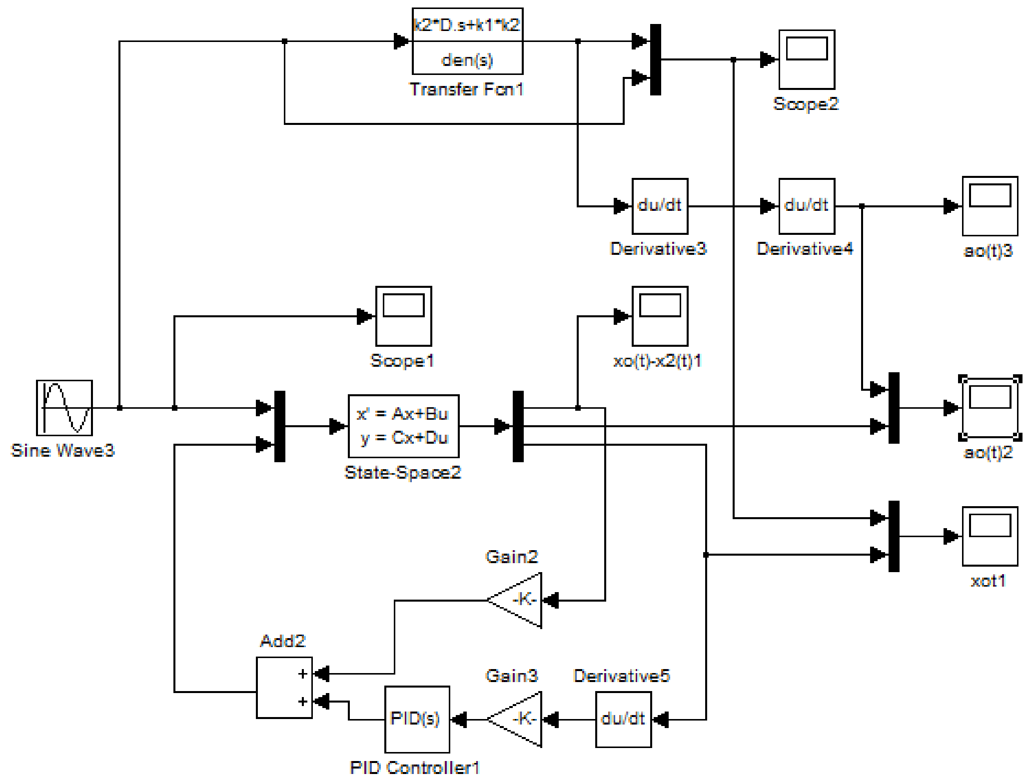


Figure 56 - New algorithm PID control active suspension system Simulink structure with the sine wave input

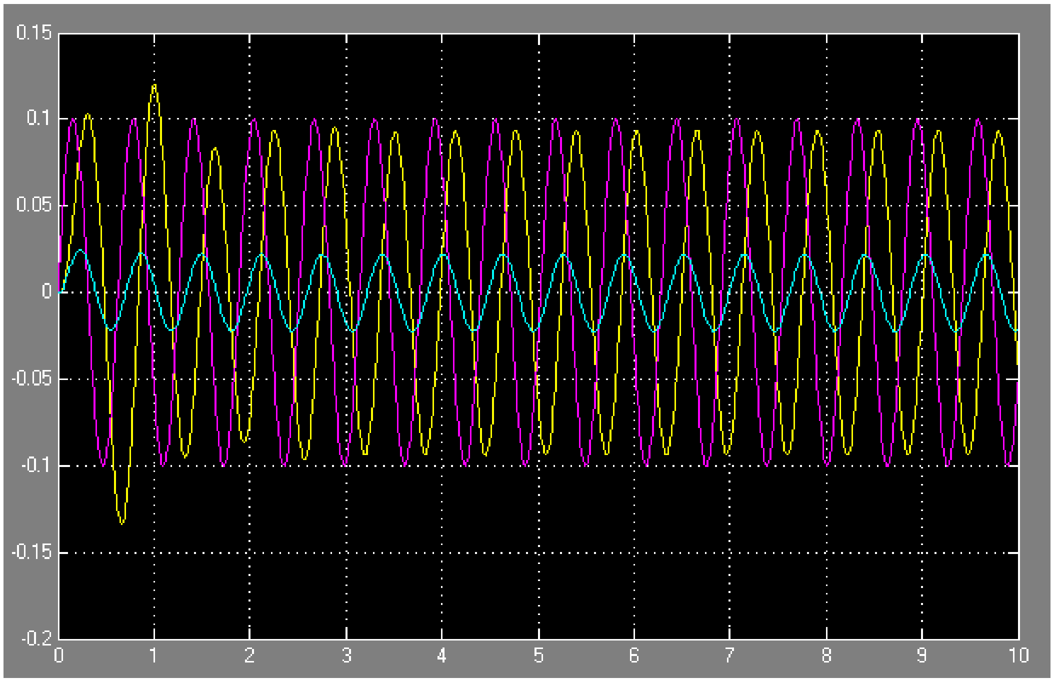


Figure 57 - New algorithm PID control active suspension system output acceleration time response with the input of sine wave signal, and compare with passive suspension

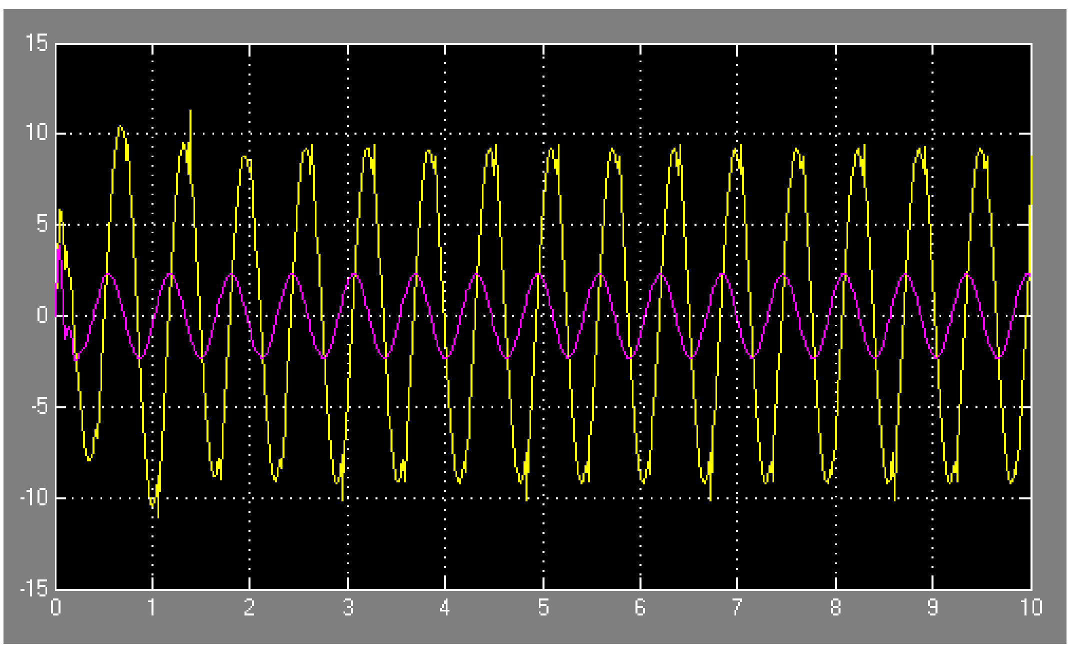


Figure 58 - New algorithm PID control active suspension system output acceleration time response with the input of sine wave signal, and compare with passive suspension

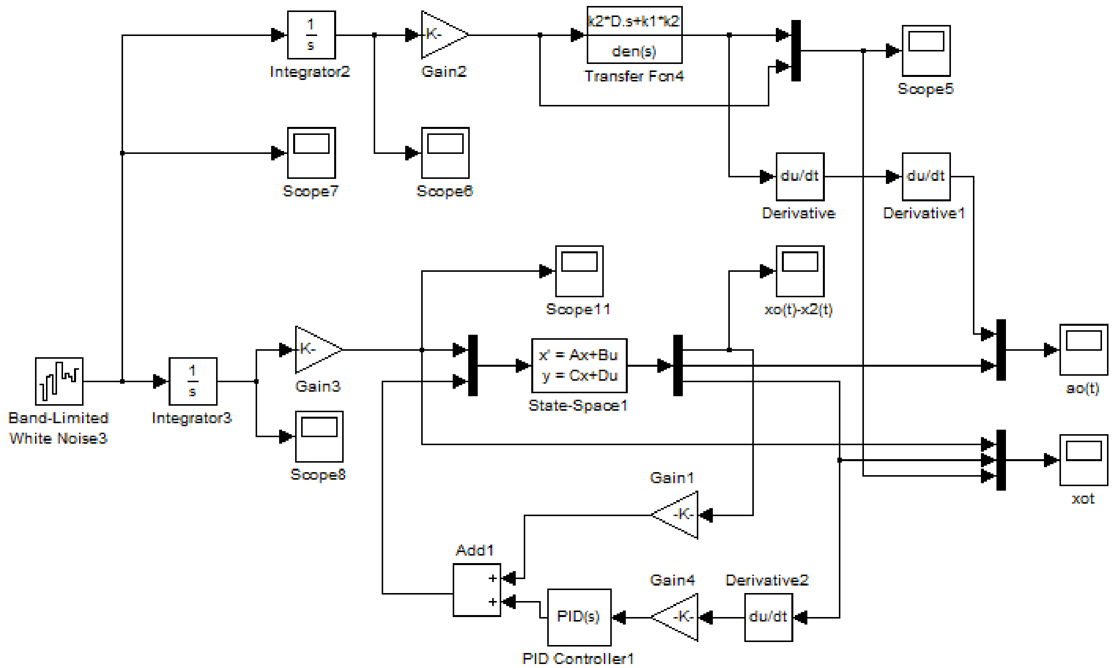


Figure 59 - New algorithm PID control active suspension system Simulink structure with the white noise input

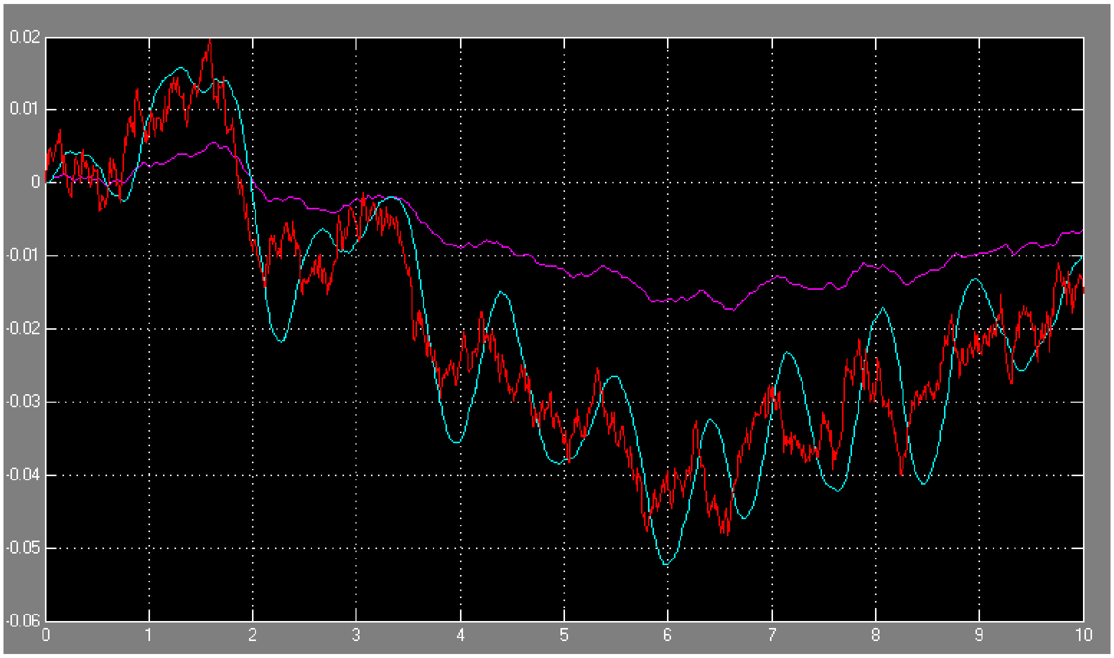


Figure 60 - New algorithm PID control active suspension compare with passive suspension system output displacement time response with the input of white noise signal

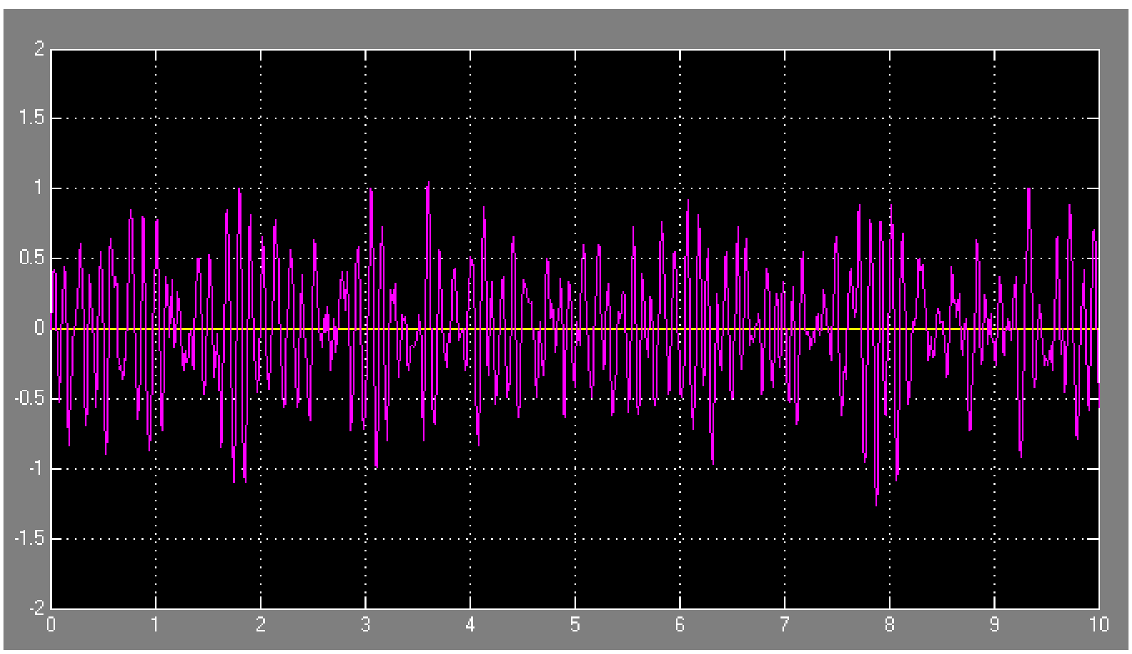


Figure 61 - New algorithm PID control active suspension system output acceleration time response with the input of white noise signal

From figure 53 to 61, we can see that new algorithm PID control active suspension system has made some improvement from new algorithm active suspension control system. The output displacement and acceleration is further reduced. The reliability and stability is further increased. The Curves is more flat than every control methods' curves.

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

The thesis begins at preface and introduction. Suspension system is the most significant part which heavily affects the vehicle handling performance and ride quality. Chapter 2 gives us an original understanding of three types of suspension system-passive suspension system, active suspension system, and semi-active suspension system. This thesis is focused on suspension control systems and control methods. Chapter 3 established each mathematical model of the passive suspension system and active suspension system. It also makes three kinds of pavement input signal and creates suspension performance evaluation standard. Chapter 4 proposed three types of control methods and make math model separately. Chapter 5 makes Simulation modeling structures and did simulation result analysis.

According to the result analysis made by Chapter 5, this several control methods each has its own characteristics. We cannot simply say which kind of the three control systems is better, such as PID control method dramatically decreased the vibration, but increased the acceleration; pavement feedback control method has actually good performance by using white noise signal, but fail by using the other two signals; new algorithm has the best performance, but it has no experience to test in the real world. But we can see that the method of combination of PID control and new algorithm is more competitive, it has shown best stability and reliability. This combination also greatly improves the displacement and acceleration characteristics, and the curve is more smoothly, which achieved great effect. This new type of intelligent control strategy provides a new idea to automotive active suspension control theory research. At the same time this thesis proves the feasibility of the new algorithm, and laid the groundwork for further research.

6.2 Future Work

Through the author's research and computer simulation to vehicle active suspension control system, the following aspects could be the breach of the further research of this problem:

1. The top advantage of the computer simulation is convenient to operate, but its disadvantage is also very obvious, which the simulation results are not withstand the actual test. The next step is to use experiment devices to test and verify the simulation results. This process can further improve the simulation methods.

2. To research the suspension system itself, this thesis only established ¼ vehicle math models and only got the vertical displacement and acceleration outputs. The next step is to establish ½ vehicle system model, the whole vehicle model, and even add the Passengers and driver seat model. Through these models, we can analyze the vehicle

pitching, rolling, and yawing movement, and get the passengers and driver's real displacement and acceleration.

3. This thesis only combine the PID control method and new algorithm method together, but not combine with pavement feedback system. The next step is find a way to combine them together and also combine with the latest advanced control technology. Through this way, the active suspension control system will be more complete.

4. In the automobile industry fields, now the research direction is to combine active suspension system, ABS, steering system and driving system together. So the next step is to research the control method of the above methods. And this problem has now become the research hot spot.

5. This thesis author does not discuss which type of actuator the suspension system should use. In order to achieve this thesis control methods, in the next step, we need to analyze the power requirement of the actuator, and further recognize the real world limitation.

6. This thesis author considers the active suspension's actuator action as transient response, but in the real world, the response delay should be put into consideration. So the next step is to build a real world mathematical model of the active suspension actuator, which can reflect the real physical characteristics and response.

7. This thesis uses pavement feedback control system but it is not perfect enough, and in the next step, pavement monitoring system should combine with the control feed

forward theory, so that the vehicle suspension actuator can take actions before road disturbance go through the vehicle tire.

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APPENDIX: MATLAB PROGRAM EXAMPLES

```
%
% Script file: Passive_simulation.m
%
% Purpose:
% Simulate the passive suspension system movement when the signal input
is
% unit step input.
%
% Record of revisions:
%  Date         Programmer  Description of change
%  =========    ==========  =====================
%  1/23/2013     Qi Zhou     Original code
%
% Define variables:
%  k1 -- stiffness coefficient, N/m
%  k2 -- vehicle tire stiffness coefficient, N/m
%  D  -- average damping coefficient, N*s/m
%  m1 -- sprung mass, kg
%  m2 -- unsprung mass, kg
%

%clear all;
clc;

k1=15000;
k2=150000;
D=1000;
m1=300;
m2=40;

num=[0,0,0,k2*D,k1*k2];
den=[m1*m2,(m1+m2)*D,m1*k1+m1*k2+m2*k1,D*k2,k1*k2];
step(num,den);
grid
```

```
%
% Script file: Passive_simulation.m
%
% Purpose:
% Determine the Semi-active suspension damping coefficient
% with the change of the road roughness.
%
%
% Record of revisions:
%  Date         Programmer  Description of change
%  =========    ==========  =====================
%  2/1/2013     Qi Zhou     Original code
%
% Define variables:
%  k1 -- stiffness coefficient, N/m
%  k2 -- vehicle tire stiffness coefficient, N/m
%  D  -- Semi-active suspension damping coefficient, N*s/m
%  m1 -- sprung mass, kg
%  m2 -- unsprung mass, kg
%

% clear t;
clc;

k1=15000;
k2=150000;
m1=300;
m2=40;
D(102)=0;

for n=1:1:102
    if abs(wta(n))>=0.25
        D(n)=500;
    elseif abs(wta(n))<0.25
        D(n)=1500;
    end
end
```

```
%
% Script file: plotPSD.m
%
% Purpose:
% Plot PSD and with the change of space frequency
%
% Record of revisions:
%  Date         Programmer  Description of change
%  =========    ==========  =====================
%  1/22/2013     Qi Zhou     Original code
%
% Define variables:
%  f --space frequency
%  PSD -- Road Power Spectral Density
%

clear all;
clc;

Gqn0=6.4*10^(-5);
v=20; %(unit: m/s)
n0=0.1; %(unit: /m)
w=2;

f=0:1:100;
PSD=Gqn0.*n0.^2*v./f.^2;
%PSD=(12.8*10^(-6))./f.^2;
loglog(f,PSD);
title('Space frequency VS Road PSD');
xlabel('Space frequency (Hz)');
ylabel('PSD')
grid on;
```

VITA

Qi Zhou, the son of Zhaoxi Zhou and Shukun Tian, was born in Beijing, China on Dec. 29th, 1987. After graduated from the high school attached to Tsinghua University in 2006, he entered University of Science and Technology Beijing. He received a Bachelor of Science Degree in the major of Automotive Engineering in 2010. He started his graduate education in the Department of Mechanical Engineering and Mechanics at Lehigh University in September 2010. Currently he has achieved his requirements for his Master of Science Degree and will graduate on May 2013.