

## Modeling and Simulation of PID Controller-Based Active Suspension System for A Quarter Car Model

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### ABSTRACT

The most common automotive suspension systems have been used passive components with fixed damping coefficient and spring constant. They are two separate functions to reach a compromise between drive quality and handling performance. Because of the limit of structures, the passive suspension system could hardly enhance the two features at the same time. In recent years, the active suspension system has been widely used in a vehicle which can overcome the limitations of the passive suspension systems. Since there are many advantages to make the vehicle operate safer and quieter than the passive suspension system. The aim of this study is to develop a linear mathematical model of active and passive suspensions systems for quarter car models subjected to different road profiles using a Proportional Derivative Integral (PID) controller. After modeling and simulation of the suspension system using Matlab/Simulink, this study has been able to determine the parameter of PID controllers of active suspension in many different road surfaces and vehicle speeds to improve driving comfort. Another new point of this study is the Graphical User Interfaces to be a successful design. The users can enter the input parameters for Matlab processing and get the results, which can make system analysis faster and more convenient. The main outcomes of this paper are performed to investigate and compare the response between active and passive suspension systems. Through the analysis of the simulation results, this research has demonstrated the feasibility, reliability, and they can be applied to propose a further improvement of the kinematic and dynamic characteristics of the vehicle active suspension system.

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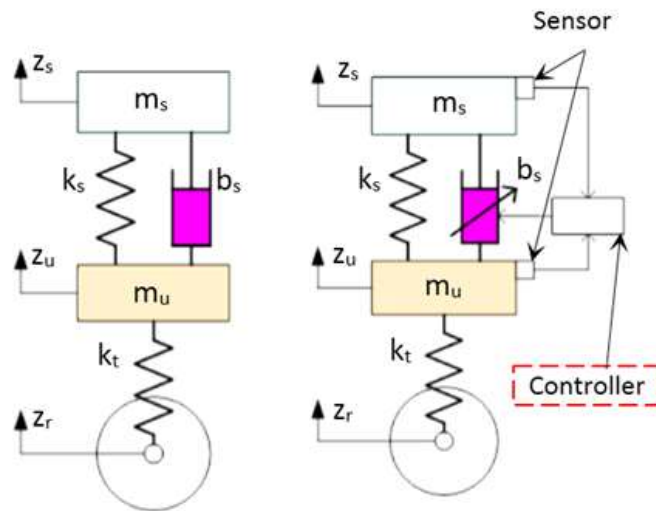
### 1. Introduction

A vehicle suspension is the utmost important system that is required to perform in comfort and safety under different operating conditions such as cornering, braking, and accelerating at high levels of speed. The principle requirements are to provide handling performance and a good ride from tire force excitation. Besides, it can be prevented the transmission of a road surface to the vehicle body. Because of structural limitations, the passive suspension system is hard to satisfy all properties at the same time. Active suspension with advanced control technologies was introduced to overcome the limitations of earlier systems [1-5].

Vehicle suspensions can be classified into three basic types: passive, semi-active, and active suspension systems, which depends on the operation mode to provide good drive handing capability, to enhance the stability of driving, and to minimize the road damage.

The passive suspension is a conventional system that cannot be adjusted the stiffness and damping coefficient, and without any actuator and additional power as shown in Fig. 1a. Due to the traditional mechanical structure, it is very hard to adapt to different types of road conditions. To acquire good ride comfort and handling stability at the same time, it can only design for specific operating conditions [2]. Similar to the conventional type of suspension systems, a semi-active suspension system contains one spring and damper with a controllable damping coefficient. Because of the limitations of a controllable

damper, this mechanism can also be converted where the damper is fixed, and spring is controllable as illustrated in Fig. 1b. The existence of semi-active suspensions is more practical than ever in engineering realization [2-6].



**Figure 1.** Illustration of a quarter-car model of a typical suspension system  
(a) Passive suspension (b) Semi-active suspension

Typically, active suspension can be represented diagrammatically as shown in Fig. 3. Because of the ever-increasing demands on vehicle performance, the automotive active suspension system has been launched to control their body movement according to vehicle load and road conditions. The functions of conventional passive elements such as spring and damper have been replaced by a controllable actuator. The potential benefits of controllable suspensions are not improving the individual performance at each wheel station, but also the possibility of giving generally improving vehicle safety.

In this paper, the actual vehicle can be modeled into a quarter car model. The simulation results can get the output control parameters of the automatic control block such as  $K_p$ ,  $K_i$ ,  $K_d$ , and give us the vertical oscillation parameters to evaluate the system's oscillation performance compared to ISO standards. A PID (Proportional Integral Derivative) controller is a control loop mechanism employing feedback that is widely used in industrial control systems. In this study, the PID controller is used to control the actuator force of the active suspension system. The Graphical User Interface (GUI) is conducted to determine the parameter of PID controller of the active suspension system. Furthermore, the manual tuning solutions of PID controller can be applied to control reactive force in a specific automotive active suspension system.

## 2. Problem Identification and Methodology

To model the active suspension system, the linear quarter car model can be developed as in Fig. 2, where  $k_s$  and  $k_t$  are the spring stiffness and tire stiffness respectively,  $b_s$  is the damping coefficient,  $F_a$  represents the force produced actuator.  $z_s$  and  $z_u$  represent the vertical displacements of the sprung mass ( $m_s$ ) and unsprung mass ( $m_u$ ) respectively,  $z_r$  represent the vertical displacements of the road [3, 14-18]. In a passive suspension, the active force  $F_a$  can be set to zero.

**Table 1.** Parameter values of suspension system

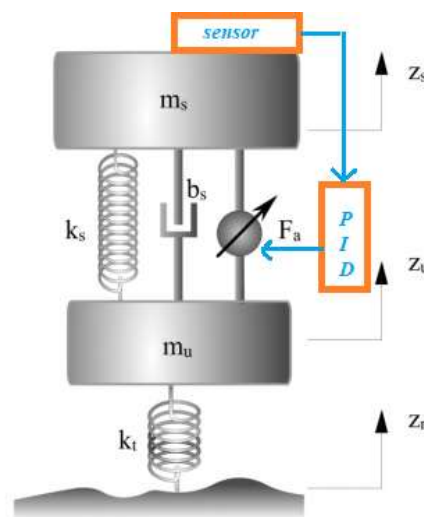
Vehicle Mode Parameters (unit)	Values
$m_s$ (kg)	250
$m_u$ (kg)	50
$k_s$ (N/m)	18,600
$k_t$ (N/m)	196,000
$b_s$ (Ns/m)	1,000
V (km/h)	40

Where,  $V$  is speed of vehicle.

When there is a force exerting from the road surface on unsprung mass through the stiffness of the tire spring in the upward direction. Through the stiffness spring and damping coefficient of the suspension acting on sprung mass make this mass move up. However, when the actuator force is applied, this actuator force will act a reverse force helps the sprung mass limit movement. The result makes sprung mass fluctuate very little.

Table 1 shows parameter values of suspension system for quarter car model, the parameter of type of road input- degree of roughness with road class C, and vehicle speed of 40 km/h. The quarter-car linear dynamic model was proposed based on the following assumptions [19]

1. The longitudinal effect of road profile can be considered negligible.
2. Slip between the tires and road surface was ignored.
3. There is no effect of the air force.
4. There is no influence of bearing-free gap and lubricant membrane.



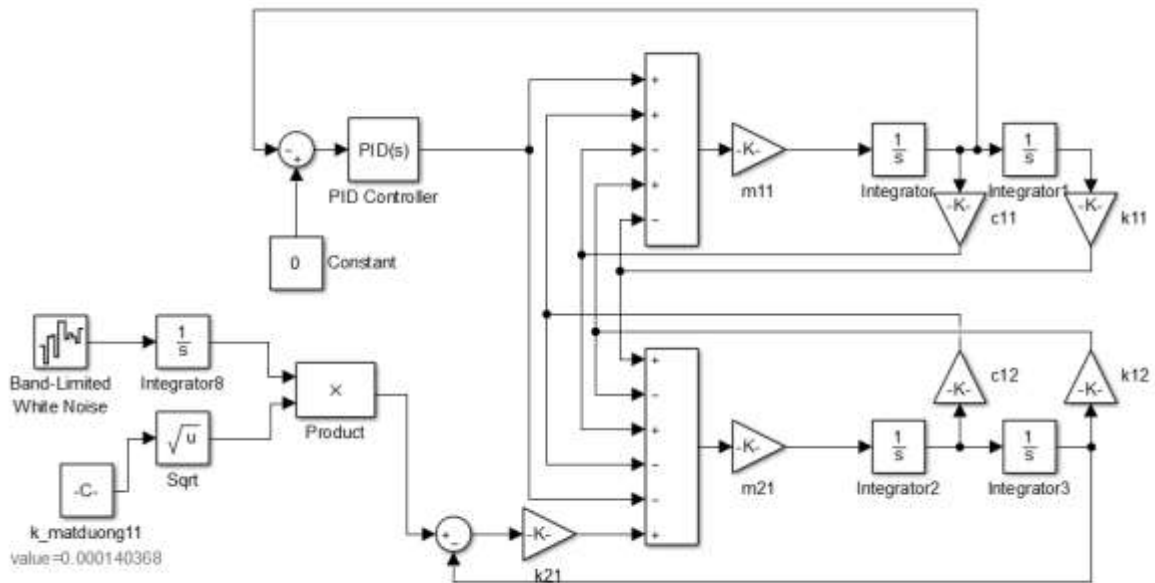
**Figure 2.** Quarter-car model of active suspension [2]

Applying Newton's second law in the active suspension system, the equations of motion are written as:

$$\begin{cases} m_s \cdot \ddot{z}_s = -k_s \cdot (z_s - z_u) - b_s \cdot (\dot{z}_s - \dot{z}_u) + F(t) \\ m_u \cdot \ddot{z}_u = -k_s \cdot (z_s - z_u) + b_s \cdot (\dot{z}_s - \dot{z}_u) - k_t \cdot (z_u - z_r) - F(t) \end{cases} \quad (1)$$

$$\begin{cases} \ddot{z}_s = \frac{1}{m_s} (-b_s \cdot \dot{z}_s + b_s \cdot \dot{z}_u - k_s \cdot z_s + k_s \cdot z_u + F(t)) \\ \ddot{z}_u = \frac{1}{m_u} (b_s \cdot \dot{z}_s - b_s \cdot \dot{z}_u - k_t \cdot z_u + k_t \cdot z_r + k_s \cdot z_s - k_s \cdot z_u - F(t)) \end{cases} \quad (2)$$

From the equations of motion (2), the simulation model of the active suspension system can be conducted in the Matlab/Simulink with blocks function as shown in Fig 3.



**Figure 3.** Simulink model of active suspension system

The input signal of PID controller is the velocity of the sprung mass. The error is a result of subtraction of velocity of sprung mass and setpoint (0). When the error appears the PID controller will control the actuator force (output signal) effect on two mass and make the error to the setpoint is zero.

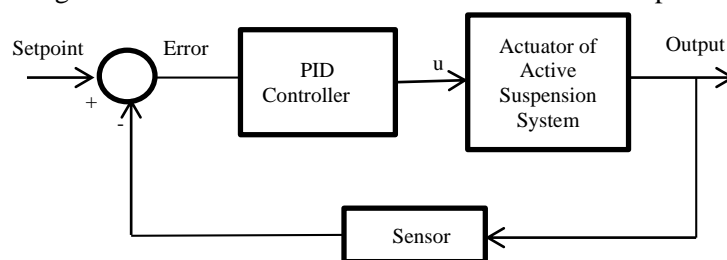
### 3. Control Algorithm Design of Active Suspension System

#### 3.1. PID Controller

The principle of operation of the PID controller is based on a closed-loop control system. PID stands for P (proportional), I (integral), D (derivative). In proportional (P) control output signal will be got by multiplying the current error signal with gain ( $K_p$ ).

The integral sign is the sum of all the instantaneous values that the signal has been from whenever you start counting until u stop counting. When integral term adds to proportional term accelerates the movement of the process towards set-point and eliminates the residual steady state error that occurs with a proportional controller.

The derivative term slows the rate of the controller output and this effect is most noticeable close to the controller set-point. Fig. 4 shows the PID controller used in the active suspension system [20].



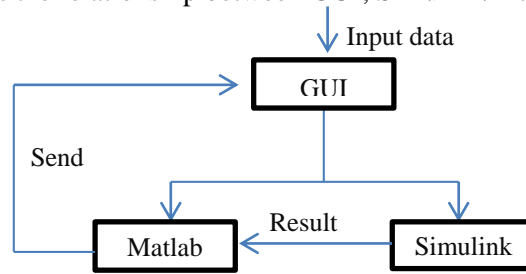
**Figure 4.** Block diagram of suspension system using PID Controller

#### 3.2. Graphical user interfaces

Graphical user interfaces (GUIs), also known as the application, provide point-and-click control of your software applications, eliminating the need for others to learn a language or type commands to run the application.

In this paper, the GUIs is designed to help the author or anyone who wants to study and find the parameters of the PID controller of the active suspension. It is the place to change the input parameters, invoke commands from Simulink and Matlab to trigger simulation from Simulink, and run the .m files.

Then output the results and send back the GUI to display the results as parameters, graphs to evaluate the suspension. Figure 5 shows the relationship between GUI, Simulink/Matlab, and Matlab.



**Figure 5.** Relationship between GUI, Simulink/Matlab and Matlab

### 3.3. Control Algorithm Design

The control algorithm of quarter-car dynamic model is designed based on the following requirements:

1. Maximum Suspension traveled not over 0.1m for this work [4, 13].
2. Car body acceleration become minimum.

The Fig. 6 shows the control algorithm design of the active suspension system is a general algorithm to find parameters of PID controller with manual way by loop programs. Graphical user interface is an interface that authors build to get parameters of PID controller of active suspension.

Parameters  $K_p$ ,  $K_i$ ,  $K_d$  can be determined through the loop. Let  $K_p$ ,  $K_i$ ,  $K_d$  get from 0 to n where n is the limitation of those parameters. The parameter response the conditions of the suspension system will be saved and continue for the forward parameter set, if the following set of parameters response better, then it continues to save. The final result will give the best response set of parameters  $K_p$ ,  $K_i$ ,  $K_d$  in the range of the suspension system.

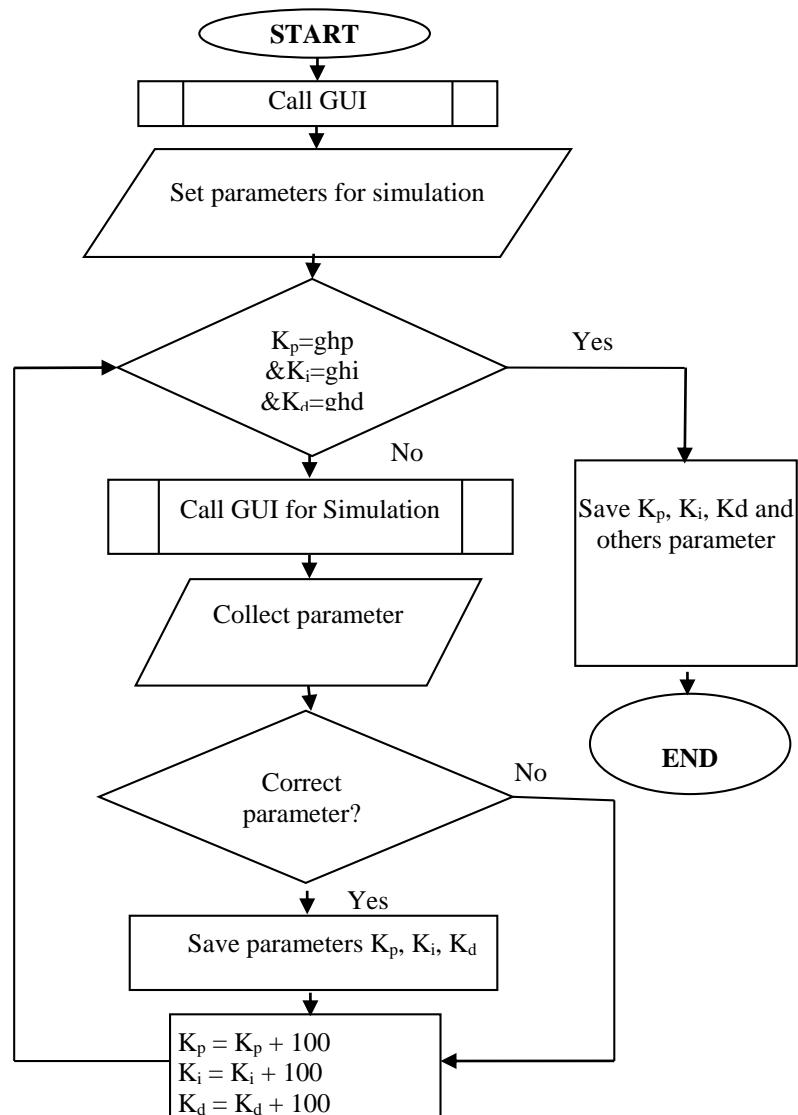
### 4. Results and discussion

Driving quality can be assessed by the vertical acceleration of passenger locations. Sprung mass acceleration  $Z_s$  can be used to evaluate the drive quality of the active suspension system [3] so that advanced control techniques, such as PID controllers have been provided to reduce the vibration of a vehicle body. International Standard ISO 2631-1 has chosen to quantify suspension system is shown in Table 2 [5].

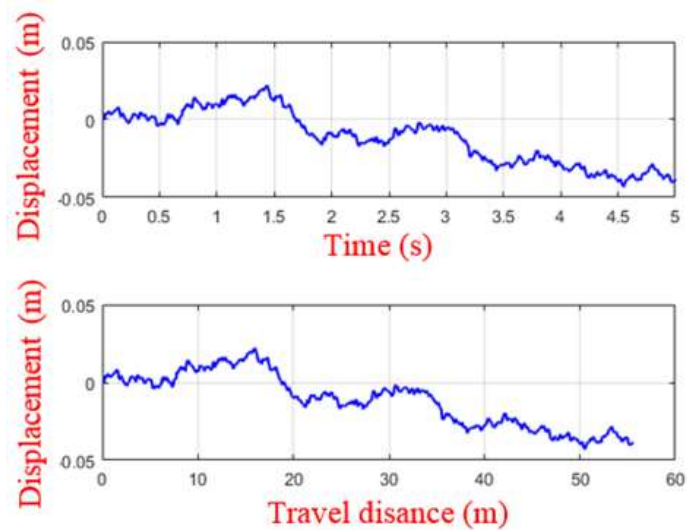
**Table 2.** Approximate indications of likely reaction to various magnitudes of overall in public transport [5]

Values (unit)	Feature
$\leq 0.315$ (m/s <sup>2</sup> )	Not uncomfortable
0.315 – 0.63 (m/s <sup>2</sup> )	A little uncomfortable
0.5 - 1 (m/s <sup>2</sup> )	Fairly uncomfortable
0.8 – 1.6 (m/s <sup>2</sup> )	Uncomfortable
1.25 – 2.5 (m/s <sup>2</sup> )	Very uncomfortable
$\geq 2$ (m/s <sup>2</sup> )	Extremely uncomfortable

The input road profile is selected in Mechanical Vibration - Road surface profiles - Reporting of measured data ISO 8608:1995 [6-9]. The input road profile is simulated road class C and vehicle speed of 40 km/h and as shown below in Fig. 7.



**Figure 6.** Control algorithm design of active suspension system



**Figure 7.** Input road profile

User input data of suspension, road class, and vehicle speed into GUIs to determine parameters of PID controller as shows in Fig. 8.



Figure 8. GUI for determining parameters of active suspension system

After running up the program, the parameters of the PID controller can be obtained as shown in Table 3. It can be controlled by the active actuator force  $F_a$  to support the system to work more efficiently.

Table 3. Parameters of PID controller

Parameter	Value
$K_p$	5,870
$K_i$	100
$K_d$	1,300

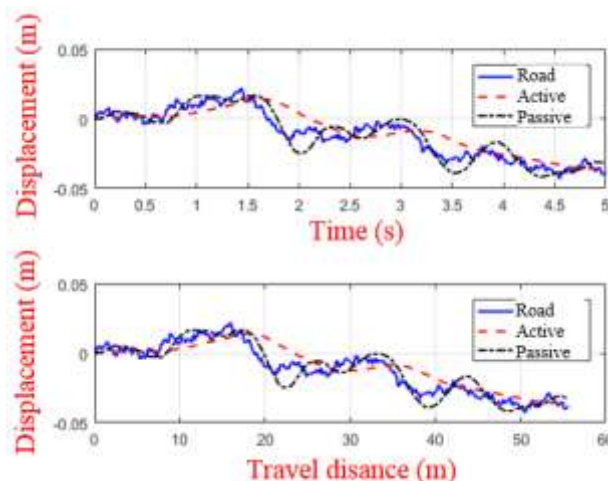
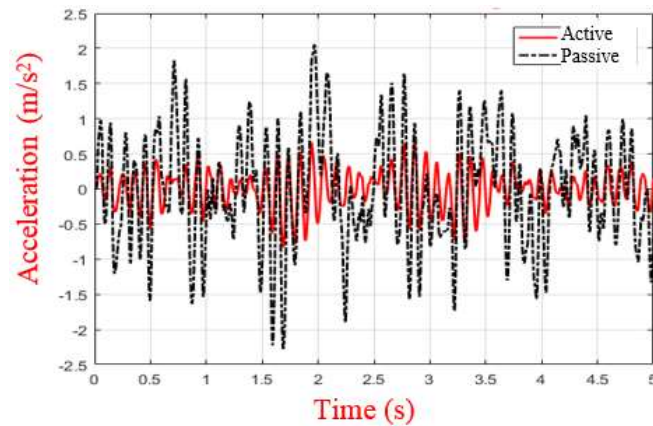


Figure 9. Car body displacement

With the same input parameters of the passive and active suspension system, the different responses between the passive and active suspension system can be seen in Fig. 9. The car body displacement of active suspension vibration less than that of passive.

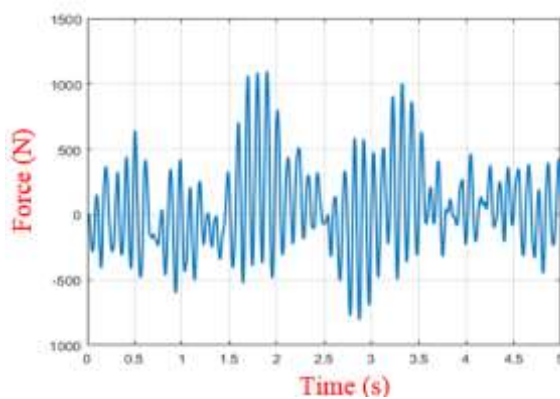


**Figure 10.** *Passive vs. Active sprung mass vertical acceleration*

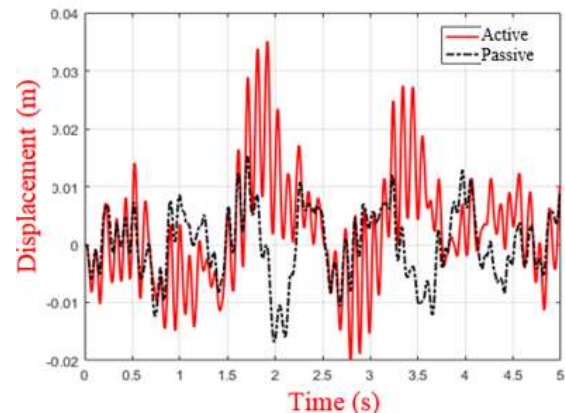
Figure 10 shows the sprung mass vertical acceleration of active suspension less than that of passive suspension. According to the ISO 2631-1 if sprung mass vertical acceleration is less than  $0.315 \text{ m/s}^2$  then passengers in vehicles are not uncomfortable, from  $0.315$  to  $0.63 \text{ m/s}^2$  will be a little uncomfortable [5, 10-13].

For passive suspension, these values greater than  $0.63 \text{ m/s}^2$  make the passengers are rarely uncomfortable. An active suspension system with PID controller has a value less than  $0.315 \text{ m/s}^2$  make the passengers are not uncomfortable. The sprung mass displacement has been reduced by 65% with the active suspension.

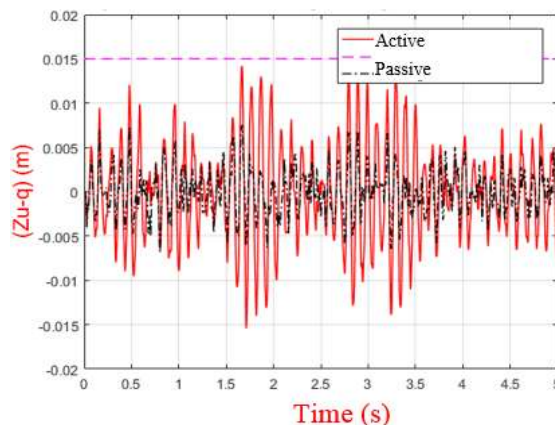
With parameters, PID Controller controls the active actuator force  $F_a$  support to active suspension. That can be shown in Fig. 11. The maximum force is 1,100 (N) which is not too large to active the system.



**Figure 11.** *Actuator control force of active suspension system.*



**Figure 12.** *Passive vs. Active Suspension displacement*



**Figure 13.** *Passive vs. Active wheel displacement*

Suspension and wheel displacement of both passive and active suspension systems as shown in Fig. 12 and 13. In active suspension, the spring must work more to enhance drive quality. But wheel displacement less than the limitation of the wheel means that wheel until contact with road surface profile. With GUIs, we can find parameters of the PID controller at different speeds and different road classes as shown below in Table 4 and 5. In reduction, the column is sprung mass vertical acceleration active subtract passive and per sprung mass vertical acceleration.

**Table 4.** Parameters of PID controller at C road class

Speed (km/h)	$K_p$	$K_i$	$K_d$	Reduction (%)
10	11,000	5,000	5000	82.9
20	11,000	5,000	5000	85.7
30	9,700	900	3400	81.5
40	5,870	100	1300	65
50	10,870	3,000	1200	68.6
60	10,870	3,000	1200	60
70	6,000	400	1700	75.5
80	3,540	400	500	52.6
90	1,010	100	500	50.3

**Table 5.** Parameters of PID controller at different road class

Road class	Speed (km/h)	$K_p$	$K_i$	$K_d$	Reduction (%)
A	10	11,000	0	5,000	82.9
A	40	9,420	2,200	5,000	84
A	70	10,980	4,900	5,000	88.6
A	110	10,740	2,400	5,000	88.8
D	40	9,000	100	5,000	83.8
E	20	10,000	0	5,000	85.6
F	10	2,020	900	1,200	63.4

The parameters of PID Controller can be used to establish a PID controller to control active suspension system with vehicle operate at different road surface profile and different vehicle speed.

It must be consistently used International System of Units (SI Units) for the data in the article. Other kinds of unit should be converted to SI units whenever possible. Italic format is applied for symbols of calculated quantities. Decimals presented in Vietnamese articles by "," and by "." in English articles.

## 5. Conclusions

In this paper, the methodology was developed to design and determine the parameters of the PID controller of the active suspension system. The Mathematical modeling of the quarter car model has been conducted using a two degree of freedom system to assess the performance of suspension concerning various contradicting requirements. By using Matlab/Simulink, the simulation results are illustrated that active suspension system reduced the sprung mass displacement and sprung mass vertical acceleration 65% in the case of road class C at a vehicle speed of 40 km/h, 88.6% in the case of road class A at a vehicle speed of 70 km/h. In a condition of road class C at a vehicle speed of 40 km/h. In a passive suspension system, the sprung mass vertical acceleration is  $0.78 \text{ m/s}^2$  greater than  $0.63 \text{ m/s}^2$  make the passengers are rarely uncomfortable. However, with an active suspension system, the sprung

mass vertical acceleration of  $0.28 \text{ m/s}^2$  makes the passengers are not uncomfortable. The parameters of the PID controller can be determined by GUI that makes to reduce the sprung mass vertical acceleration of active suspension in comparison with passive suspension in every speed and different types of road profiles.

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