ISSN: 2617-2070 (Print) ; 2617-2070 (Online)
Journal of Advanced Sciences and Engineering Technologies
available online at: http://www.jaset.isnra.org

Journal of Advanced Sciences and Eng. Technologies
JASET

Mohammed H. Mohammed [1]

Adel M Bash [2]

[1] Department of Mechanical Engineering/
Tikrit University/Iraq
[1]mh805540@gmail.com

[2] Department of Mechanical Engineering/
Tikrit University/Iraq
adelbash@yahoo.com

PID Controller of Quarter Car Model of Active Suspension System

***Keywords*:**
Suspension,
Quarter car model,
Active suspension,
Passive suspension,
PID controller

ARTICLE INFO

Article history:
Received 01 jan 2018
Accepted ***15-Jan-2019***
Available online 02 febuary 2019

DOI:
http://dx.doi.org/10.32441/jaset.02.01.01

ABSTRACT

A Suspension system can be defined as the mechanism that physically separates the car body from the car wheels. The purpose of any suspension system is to increase the ride comfort, road handling and stability of closed loop system. The suspension design must be compensate the effect of conflicting criteria of road holding, load carrying and passenger comfort. An active suspension system has been proposed. A quarter-car two degree-of-freedom (2DOF) system is designed and constructed to simulate the actions of an active quarter car suspension system. White noise input is introduced to a given system to expressed unpaved road and both step input and sine wave input are studied as well. The control strategy is based on two degree of freedom PID controller. (MATLAB/ Simulink) is used to verify the proposed algorithm. The comparison between the passive and active suspension and the results obtained from a range of road input simulations in the proposed algorithm shows the effectiveness of the proposed algorithm and best results are obtained.

Introduction

The design of car advanced system has been improved efficiently since the last three decades using individual control systems, algorithms and active actuators. The changing in the systems components' properties can be predicted widely which improving their efficiency, safety and comfort of the car [1]. The reduction in the induced ground variation, tire deflection , dynamic characteristics and provide ride comfort are the main characteristics in the design of passive suspension is designed [2]. The draw backs of the passive suspension design with inerter has been considered by [3]. In the vehicles, the multiple performance is required such as tire grip,ride comfort suspension deflection [4]. The semi-active and active suspensions are used in many vehicles applications. The passive suspension performance is restricted due to the absence of feedback control action. A new structure for a semi-active suspension to obtain performance specifications has been introduced by [5]. The active suspension systems have been utilized in linear and non-linear control methods for active seat [6]. The active suspension system is considered as improvement achieved in the system performance, which deliver a higher power to generate suspension forces to achieve the performance. Different models for vehicles suspension system can be understood due to their dynamical performance. There may different degree of freedom (DOF) as shown in the Fig.1.

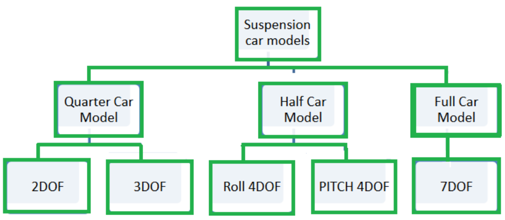

Fig.1.Classification of Suspension Models

All powers of vehicles have amount and direction depends on the size of bump that hits the wheel, where the wheels are exposed to a vertical height when passing the road curves [7]. In fact, the vehicle suspension system is part of the structure and combines all important systems at the bottom of the vehicle which includes the Frame, suspension system, guidance system [8]-[9]. Thus the system should provide appropriate conditions for increasing the ability of vehicle to change its direction and maintain a high level of quality. These are two opposites; where the process of suspension system tuning is represented by finding the right solution for the required application [10].

Independent suspension system and dependent suspension system ,are most important types of suspension systems.Dependent system allows linking all vehicle wheels with vehicle structure through suspension system so that each wheel is separated from other wheels, instead of linking the wheels with a joint axis and can be divided into front independent suspension system and rear Independent suspension system[11]. Suspension systems can be classified also depending on the type of damper used into passive suspension system, semi-active suspension system and active suspension system [12].

Passive suspension system cannot provide ride comfort and ride safety because it cannot adjust the coefficients of springs and dampers through actuators [13]-[14]. These actuators and sensors have good practical results and are significantly spreading in markets [15]. To control the semi active system, there are many strategies to maintain, the coefficient of damper used like sky-hook [16], groundhook [17] and the hybrid [18], the best strategy among these types can be found in [19].

The active suspension system consists of sensors, actuators, control unit and some hydraulic components. This system works electronically and can be controlled electronically according to the road condition in many modern vehicles, such as BMW, Mercedes-Benz and Volvo [20]. The Simulink/Matlab program has the ability to simulate and separate unspring mass from spring mass and make its power which focuses on suspension system to suit road disorder [21].The amount and power created by actuator on their effectiveness to reduce vibration resulting from the different road roughness, how actuator (PID) works on active suspension system and the influence of power on basic and rear wheels and passengers presented in[22].

The effect of road signals inputs on the ability of active control system and on reducing vibration capacity by 27.3% presented in[23].The purpose of this study is to design an active suspension system by building an actuator of 2DOFPID controller for suspension system and simulating passive and active suspension systems that were built.

MATHEMATICAL MODEL OF ACTIVE SUSPENSION SYSTEM

Develop a system good characteristics in both road holding and ride comfort is passive suspension behavior but these two indicators conflict each other and motivate different spring and damper phenomena. The considerable improvement in power consumption and variable damping characteristics will lead to the semi-active suspension systems [24]-[25].

In this work different assumptions of a ¼ car modelling are considered as follows:

1.The tires is considered as linear spring without damping,

2.The wheel and body has no rotational ,

3.There is no gap between the tire and the road surface ,

4.The friction is neglected.

for active suspension system of a 1/4 car model, parameters that describe the system are: (x(t), D, k2, k1, m2, m1, x0(t), x2(t),x1 (t)).

The suspension of the quarter car vehicle can be shown in Fig.2.

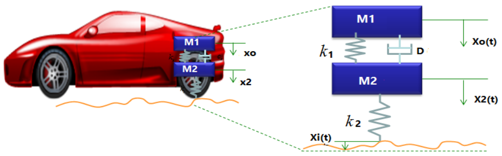

Fig.2. The suspension of quarter car vehicle

These are considered as parameters of traditional suspension system . However, what raises a question in this figure is actuator represented by (u) which gives controlled power to the system and that power has been created by actuator in active suspension system. Based on this model in Fig.2, dynamic active suspension system will be analyzed. This system is a DE with a 2DOF as in the following equations:

$$m_1 \ddot{x}_0(t) + D\left[\dot{x}_0(t) - \dot{x}_2(t)\right] + k_1\left[x_0(t) - x_2(t)\right] = u \qquad (1)$$

$$m_2 \ddot{x}_2(t) - D\left[\dot{x}_0(t) - \dot{x}_2(t)\right] + k_1\left[x_2(t) - x_0(t)\right] + k_2\left[x_2(t) - x_1(t)\right] = -u \qquad (2)$$

$$x_1 = x_2(t), x_2 = x_0(t), x_3 = \dot{x}_2(t), x_4 = \dot{x}_0(t) \qquad (3)$$

System state space can be written in this way:

$$\frac{dX}{dt} = AX + BU \qquad (4)$$

Variables of state space can be written in the form of a matrix(A) which is a system matrix and matrix (B) is input matrix are:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1+k_2}{m_2} & \frac{k_1}{m_2} & -\frac{D}{m_2} & \frac{D}{m_2} \\ \frac{k_1}{m_1} & -\frac{k_1}{m_1} & \frac{D}{m_1} & -\frac{D}{m_1} \end{bmatrix} \quad (5)$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{k_2}{m_2} & \frac{1}{m_2} \\ 0 & -\frac{1}{m_1} \end{bmatrix} \quad (6)$$

System variables introduced to the matrix are:

$$U = \left[x_i(t) \;\; u\right]^T \quad (7)$$

System outputs of suspension system of vehicle in the matrix form are:

Y=CX+DU
(8)

Variables of equation (8) are

$$Y = \left\{ k_2\left[x_i(t) - x_2(t)\right] \;\; \ddot{x}_0(t) \;\; x_o(t) \right\} \quad (9)$$

Equation Y can be written as in (10)

$$Y = \left\{ k_2\left[x_i(t) - x_1\right] \;\; \ddot{x}_2 \;\; x_2 \right\} \quad (10)$$

Matrices(C) and (D) are output matrix and feedforward matrices respectively as shown below:

$$C = \begin{bmatrix} -k_2 & 0 & 0 & 0 \\ \frac{k_1}{m_1} & -\frac{k_1}{m_1} & \frac{D}{m_1} & -\frac{D}{m_1} \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (11)$$

$$D = \begin{bmatrix} K_2 & 0 \\ 0 & -\frac{1}{m_1} \\ 0 & 0 \end{bmatrix} \quad (12)$$

The transfer function(TF) of the 1/4 car model in the active suspension system can be shown as in (13).

$$G(s) = \frac{1.2e04\,s + 1.8e06}{s^4 + 28\,s^3 + 4.2\,s^2 + 1.8e06} \quad (13)$$

The parameters used in the simulation are listed in table1.

Table 1. Simulation parameters and its meaning

Symbols for suspension system	Values	Meaning	Unit
m1	300	Vehicle mass	Kg
m2	40	Excel and wheels mass	Kg
k1	15000	Spring connects the vehicle body and wheels	m/ N
k2	150000	Frame	m/N
D	1000	Damper	m/N*s

The spring and damper circuit in the suspension system can be shown in Fig.3.

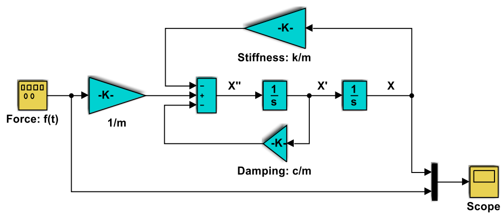

Fig.3. Block diagram of the general suspension system.

There are eight standard levels to assessment the roads optimality (A-H) as can be shown in table2. In this study, level has been chosen.

Table2.Standard levels of the roads

Road level	$(G_q(n_o)/10^{-6}m^3)$ $n_o=0.1m^{-1}$	$(\sigma_q/10^{-3}m)$ $0.01m^{-1}<$ 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

As mentioned earlier, despite the large volume of studies in this area, and although the TAM and D&M have been considered as well-recognized models in the field of IS (Gefen, et al., 2003), reviews of the most basic version of TAM routinely find that it accounts for 30% to 40% of IT acceptance, despite its relative simplicity (Lee, Kozar, & Larsen, 2003; Legris, Ingham, & Collerette, 2003). However, systematic research within the context of health care remains lacking, thus indicating a significant gap in knowledge. Therefore, developing the TAM and gaining empirical support for it within health organizations, as well as adopting a Web-based system for improving collaboration in medical research based on privacy protection, are essential. Further replication studies are necessary. In this study, we have employed qualitative research methods to support the outcome of the previous proposal and to perceive HIS acceptance problems and requirement

SUSPENSION CONTROL STRATEGY

The nonlinear control ,optimal control and back stepping control are most useful control schemes in the investigation of the 1/4 car model. Different behavioural characteristics dependent upon various road conditions should be provided by active suspension without going beyond its travel limits[26].

White noise, sine wave signal and unit step input signals are the three types that can explain road ruggedness, periodic instability and random road roughness added to the intensity of the power resulted from a hole or bump against the vehicle while driving.

The classical PID controller normally used in this field. The mathematical model of the PID controller can be expressed as in (14)

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{de(t)}{dt} \quad (14)$$

In this paper a two degree of freedom (2DoF) PID controller is used as in (15) for the mathematical model of this controller.

$$y(t) = P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}}$$

(15)

Where

N is smoothing coefficient of the filter.

Include the PID parameters with the smoothing parameters of the filter yield.

$$y(t) = 0.95213 + 0.9\frac{1}{s} + 6.4\frac{50}{1 + 50\frac{1}{s}} \quad (16)$$

The new controller composed of the classical PID and smoothing filter as can be shown in Fig.4.

In this work, the advanced PID control algorithm used Matlab/2018b features such as anti-windup, external reset, and signal tracking, tune the PID gains automatically[27].

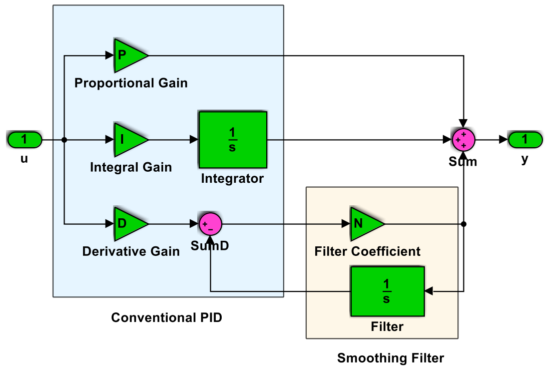

Fig.4. The advanced PID controller used.

RESULTS AND DISCUSSIONS

To understand dynamics, the quarter car model can be simulated in Matlab/Simulink to governing DE of motion for the sprung and unsprung masses of the passive and active quarter car.

The effect of white noise input on the system is simulated by Simulink implementation of the circuit shown in Fig.5.

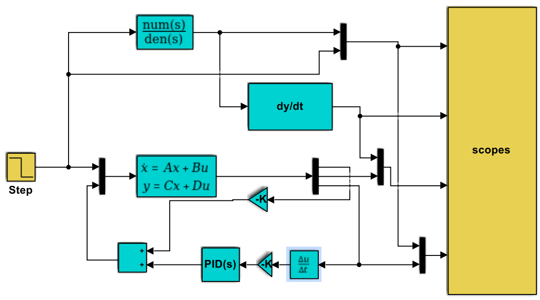

Fig.5. Simulink of the suspension system to test white noise effect

The active force of both sine wave input (smooth fluctuation road) and the step input (sudden change in the road) can be expressed as in (17)

$$u(t) = -px_i(t) \quad (17)$$

From(17), the active force (u) is relative to the road input signal xi(t) and for white noise signal(unpaved road), the equation can be transformed into (18):

$$u(t) = -p\int_{0}^{\Delta t} w_n(t)\,d\Delta t \qquad (18)$$

Fig.6 and Fig.7, shows the vehicle displacement without and with proposed PID controller for the three types of the inputs respectively. When the system passing at a constant speed, it will be exposed to random road roughness. Hence, the vibration capacity of signal resulted from passive suspension system is larger than gain represented by white noise since there is no actuator in the system. The vehicle has received these disorders routinely and put out after a long period of time; while the signal generated from active suspension system is more controlled and less vibration capacity and even less than the signal of gain and will be improved completely with the proposed algorithm as in Fig.7.

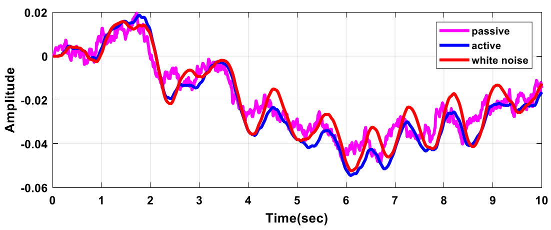

Fig.6. Suspension displacement in different situation

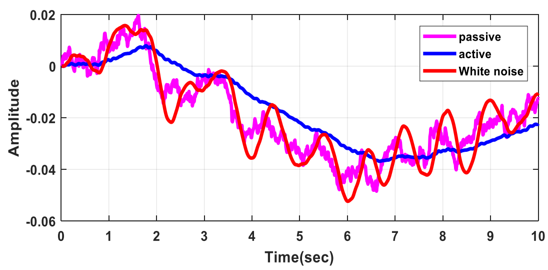

Fig.7. Suspension displacement with the white noise signal

The active suspension system acceleration response with the white noise input signal, and compare with passive suspension system can be shown in Fig.8.

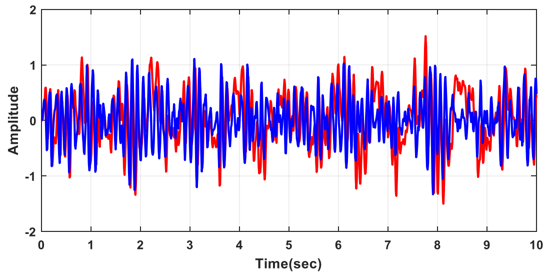

Fig.8. Active suspension acceleration response

Fig.9 and Fig.10 shows the active suspension and passive systems comparison vehicle without and with PID controller when the input is sine wave respectively. The proposed method when passing on the road with regular meanders as the signal which resulted from passive suspension system has no enough power and flexibility to withstand such fluctuations; adding to that vibration capacity is very high. However, the signal that resulted from active suspension system showed high flexibility to overcome these periodic fluctuations and vibration capacity is less than active suspension systems and it will be improved as in Fig.10 with application of the proposed algorithm.

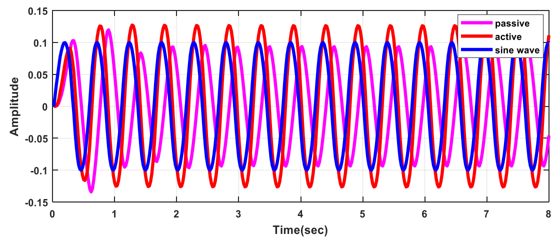

Fig.9. Active and passive suspension when subjected to sine wave in case of active

suspension

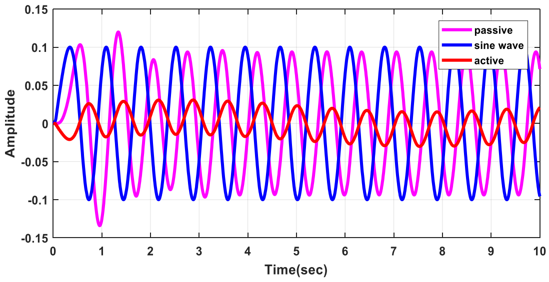

Fig.10. Active and passive suspension with the proposed algorithm

Fig. 11 and Fig.12, shows the active and passive vehicle suspension without and with the proposed algorithm when the input is step respectively. When the system passing on the road and is exposed to a jump, the signal resulted from gain of the unit step stimulates the power intensity resulted when facing a particular bump while driving. One can observe how large amplitude vibration produced by passive suspension system and compare it with vibration created by active suspension system, and then can see the vast difference in vibration capacity and again it will be improved to be more comfortable for passengers in the Fig.12.

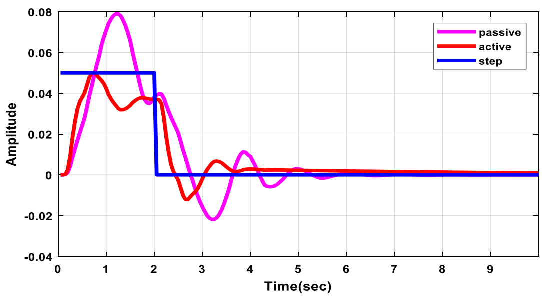

Fig.11. Active and passive suspension in step input system

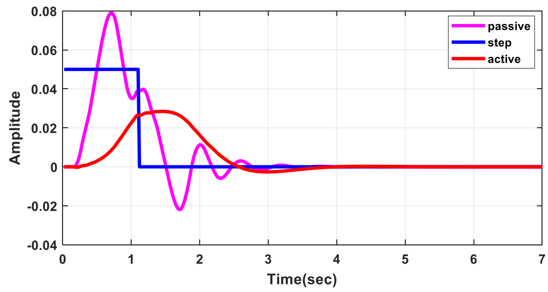

Fig.12.Active suspension compare with passive suspension displacement of unit step signal

The reduction in the acceleration value of the active suspension(red) is 50%. While the other two curve have slight change in the amplitude. The improvement in the settling time(6 sec into 2.5sec) . Small values of acceleration and displacement ensure better operation and rode comfort.

The acceleration response of the active suspension system with step input signal, and compare it with acceleration of the passive suspension can be shown in Fig.13.

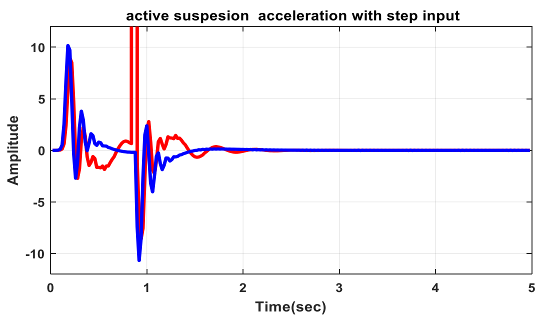

Fig.13. Active suspension system acceleration

STABILITY ANALYSIS

Stability means that the input and output signals remain bounded. This is bound input bounded output stability(BIBO). The avoidance of system instability is the main requirement for control systems with the damage preventing of the equipment. The location of the system TF poles in the s-plane is the one of the stability assessment of any linear feedback systems.

In the real systems, it is vey useful to know how the system behave against the system failure. The loop gain changing is an indication of the system rigidity before the system become unstable. The root locus plot can be used to estimate the range of (k) values for which the loop is stable as in Fig.14.

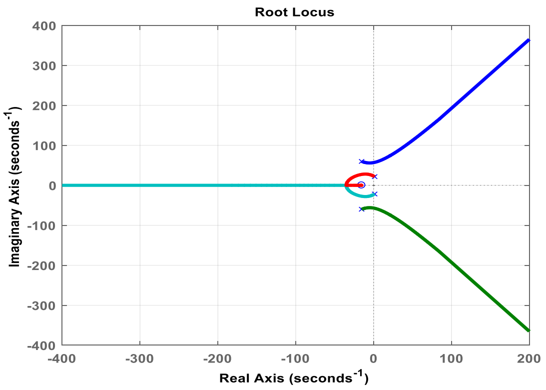

Fig.14.Root locus of the suspension system

The robust stability depends on the changing in the loop gain as one aspect to judge the system performance. If both gain and phase are unknown, the plant or system process cannot be modelled precisely. The frequency where open-loop gain is 0dB will be considered as highest errors region and it may damage the system and this occur near the gain crossover frequency combined with phase variation at this frequency[28].

The phase variation needed can be measured by the phase margin at the gain crossover frequency before the system unstability. The gain margin assesses the relative system gain needed at the gain crossover frequency before the unstability. The gain and phase margins signs is an indication of stability of the closed loop system . The highest values with positive values, refer to high system stability. The gain margin the stable closed system are(-1.07 and 116.48)dB The corresponding phase margin is (6.230 and -1000) and the peak gain to ensure stable closed loop system is 4.2dB.

The generalized proposed algorithm which contains all the suspension types is developed in this study as can be shown in Fig.15.

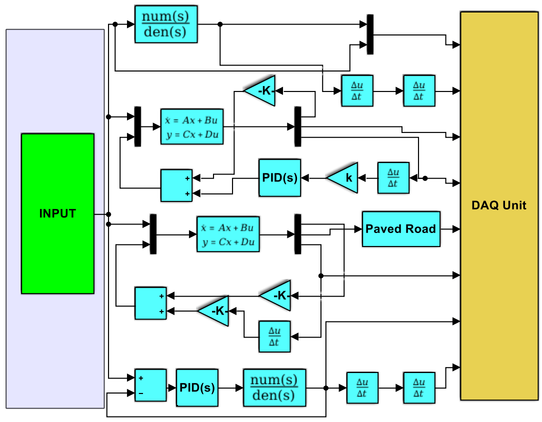

Fig.15. the complete suspension system

The vehicle with the new algorithm is tested with extra deflection to check the ride comfort in both displacement and acceleration effects, the results can be shown as in fig.16 and Fig.17. respectively.

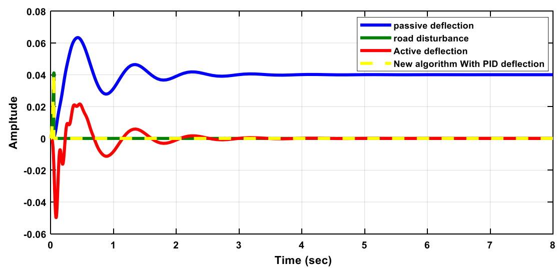

Fig.16. Displacement deflection effects on the ride comfort

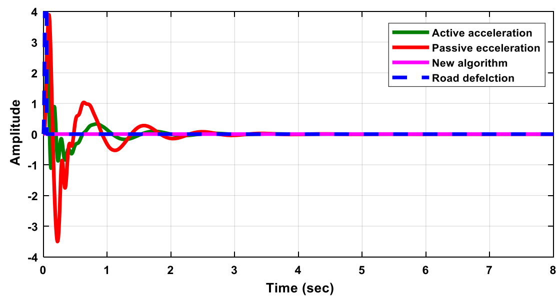

Fig.17. Acceleration effects on the ride comfort

Comparison of all the suspension systems when the input is sine wave proves that the proposed suspension system with PID controller is better than the others without PID controller as can be shown in Fig.18. for the acceleration response and Fig.19 for the displacement response respectively.

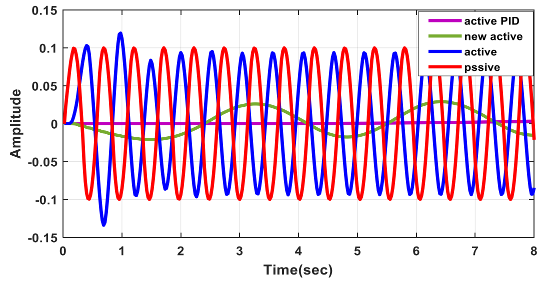

Fig.18. Acceleration response of the suspension systems with sinewave input signal

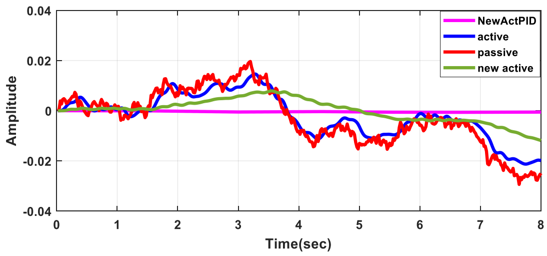

Fig.19. Displacement response of the suspension systems with sinewave input signal

With the random input signal the response proves the effectivness of the proposed algorithm as shown for the displacement response of the all suspension system. In all figures the output response of the proposed algorithm is much smaller values as an indication of the satifactory implemintaion of the new algothm in the control system techniques as can be shown in Fig.20.

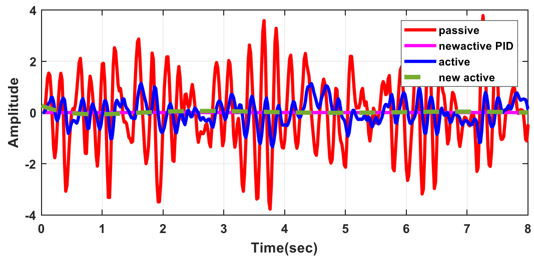

Fig.20. Displacement response of the suspension systems with randam input signal

The ride comfort can be measured as in

$$Ride\ Comfort(RC) = 20\log\left(\frac{RMS\ of\ \ the\ acceleration}{Reference\ \ Acceleration(RAcc)}\right) \quad (19)$$

$$RMS(f(t)) = \sqrt{\frac{1}{T}\int_{t-T}^{t} f(t)^{2}} \quad (20)$$

Where

f(t)),1/T is the input signal , the effective frequency respectively.

The reference acceleration (RAcc) value is (1x10-6) according to the Korean standards can be used to find the relationship between the ride comfort and the acceleration level in the suspension system as can be shown in table3.

Table 3.Ride comfort levels

RC	RC level
43	Very comfort
43-69	Comfort
69-83	Middle
83 120	Not comfort
120	Bad

CONCLUSION

Design of a sufficient and efficient suspension system is a difficult due to the conflict between the components characteristics . Active suspension system provides a greater improvement in performance of vehicle and improve ride comfort compared to traditional passive suspension systems.

By considering and expecting types of roads represented by input signals of white noise, sine wave and unit step, a new algorithm with the best performance but does not have the expertise to be tested with a practice system; however, the method of combining PID controller represented by this new algorithm with control of conventional suspension systems has the ability to compete as it has demonstrated better stability and reliability. This also dramatically improves the properties of displacement and acceleration and makes the response more smoothly.

REFERENCES

[1] D Yurlin, “Intelligent systems of the vehicles’ suspension,” OP Conf. Series: Materials Science and Engineering,2018.

[2] Hakan Yazici. Design of a Parameter-Dependent Optimal Vibration Control of a Non-Linear Vehicle Suspension System. Math. Comput. Appl.2016,21, 13.pp1-14.

[3] Hu, Y.; Chen, M.Z.Q.; Hou, Z. "Multiplexed model predictive control for active vehicle suspensions". Int. J. Control2015,88, 347-363.

[4] Chen, M.Z.Q.; Hu, Y.; Li, C.; Chen, G. Performance benefits of using inerter in semi-active suspensions. IEEE Trans. Control Syst. Technol.2015,23, 1571-1577.

[5] Zhao, Y.; Sun, W.; Gao, H. "Robust control synthesis for seat suspension systems with actuator saturation with time varying input delay".J. Sound Vib.2010,329, 4335-4353.

[6] Hrovat D., Eric Tseng H., Deur J. "Optimal Vehicle Suspensions: A System-Level Study of Potential Benefits and Limitations. In: Lugner P. (eds) Vehicle Dynamics of Modern Passenger Cars". CISM International Centre for Mechanical Sciences (Courses and Lectures), vol 582. Springer, Cham,2019.

[7] Shida Nie, Ye Zhuang, Fan Chen , Jie Xie. "Invariant points of semi-active suspensions". Advances in Mechanical Engineering, 2018, vol. 10,no.7,pp, 1-14.

[8] Kim C., Ro P. I, "An Accurate Full Car ,Ride Model Using Model Reducing Techniques", Journal of Mechanical Design, 2002, 124,pp. 697-705.

[9] P. Hsu, "Power recovery property of electrical active suspension system",Proc.31st IECEC, ,1996,vol. 3, pp. 1899-1904.

[10] J. Ma Rzbanrrad, N. Zahabi, "H Active Control of Vehicle Suspension System Exited by Harmonic and Random Roads", Mechanics and Mechanical Engineering, 2017,vol, 21, no.1, pp.171-180.

[11] Marzbanrad, J., Ahmadi, G., Hojjat, Y., Zohoor, H." Optimal Active Control of Vehicle Suspension System Including Time Delay and Preview for Rough Roads", Journal of Vibration and Control, ,2002,vol.8, pp.967-991.

[12] W.Abbas, O. B. Abouelatta, M. S. El-Azab, A. A. Megahed,"Application of Genetic Algorithms to the Optimal Design of Vehicle's Driver-Seat Suspension Model", Proceedings of the World Congress on Engineering, UK,2010, vol,11.

[13] C.L. Phillips,H. T. Nagle, "Digital Control System Analysis and Design",3rded. Englewood Cliffs, NJ: Prentice-Hall, 1994.

[14] A S. Emam, "Fuzzy Self Tuning of PID Controller for Active Suspension System", Advances in Powertrains and Automotives ,2015, vol.1, no.1, pp34-41.

[15] S.S.Khode, A.A. Satam, A.B.Gaikwad, "A Review on Suspension System of Light Commercial Vehicle", Journal of Mechanical and Civil Engineering,2017, pp. 14-19.

[16] Bo Huang. "An Energy-Regenerative Vehicle Suspension System - Development, Optimization, and Improvement". Thesis for the Degree of Doctor of Philosophy, Faculty of Applied Sciences. Simon Fraser University,2016.

[17] Mirko Coric, Josko Deur, Li Xu, H. Eric Tseng , Davor Hrovat. "Optimization of active suspension control inputs for improved performance of active safety systems", Vehicle System Dynamics,2018, vol.56,no.1,pp. 1-26.

[18] Lou, Z., Ervin,R. D., Filisko, F.E., "A Preliminary Parametric Study of Electrorheological Dampers", Trans. ASME J. Fluids Eng. ,1994,vol.116,no.3 , pp.570-576.

[19] Sankaranaray V., Emelki E. M. Guvence B. A., Guvenk L., "Semi active Suspension Control of A Light Commercial Vehicle", IEEE/ASME Transaction on Mechatronics,2008, vol. 13, no. 5.

[20] R. Jeyasenthil S.B. Choi. "A novel semi-active control strategy based on the quantitative feedback theory for a vehicle suspension system with magneto-rheological damper saturation. Mechatronics,2018, vol. 54, pp.36-51.

[21] Valasek M., Novak M., Silka Z., Vaculin O., "Extended Groundhook-New Concept of Semi active Control of Trucks Suspension", International Journal of Vehicle Mechanics and Mobility,2007. Vol.27,no.5-6,pp 289-303.

[22] Guvenc B. A., Kural E., Kesli B., Gulbudak K., Gungor S., Kanbolat A., "Semi Active Suspension Control System Development For A Light Commercial Vehicle", IFAC Proceedings Volumes,2006,vol.39,no.16,pp.391-396.

[23] Lee S., Won-Jong Kim, "Active Suspension Control with Direct-Drive Tubular Linear Brushless Permanent-Magnet Motor", IEEE Transaction on Control System Technology,2010, vol.18,no.4.

[24] Hac, A. "Suspension optimization of a 2dof vehicle model using a stochastic optimal control technique". Journal of Sound and Vibration. 100(3), (1985), pp 343-357.

[25] Wilson, D.A., Sharp, R.S., and Hassan, S.A.: "Application of linear optimal control theory to design of active automotive suspensions". Vehicle System Dynamics, 15, 2, 1986, pp 103-118.

[26] Ayman A. Aly, Farhan A. Salem. "Vehicle Suspension Systems Control: A Review". International Journal of Control, Automation And Systems,2013, vol.2, no.2,pp46-53.

[27] A.Shahriar, K.A.Rahman, S.Tanvir, "Simulation and Analysis of Half-Car Passive Suspension System", Mechanical Engineering Research Journal,2016, vol.10, pp.66-70.

[28]https://www.mathworks.com/help/control/ug/assessing-gain-and-phase-margins.html.2018.