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Improve active suspension system by FEL controller design

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1. Introduction

The cars which are moving with high speed, wide range vibration is transmitted to the passengers. Vibration category is one of the main criteria that humans can judge design and quality of vehicles. Therefore, this category is extremely important in the dynamics of the vehicle. Vehicle is a dynamic system and the disturbance of the road is transmitted to the mass body [1].

The performance of the suspension system is related to ability of vehicles. If the suspension system is more appropriate. The response road disturbances will be better. Therefore, the passengers will be more comfortable. In this system, road vibrations will be controlled and ride comfort, steering and stability of the vehicle can be supplied [2-4].

Active vehicle suspensions have attracted a large number of researchers in the past few decades that many of the limitations of passive suspension system have been solved. In 2012, Rajeswary and colleagues [5], are designed a neural fuzzy controller to improve the performance of active suspension systems. In 2011, Kamalakannan and colleagues [6], are studied the performance of characteristics of semi-active suspension system with adaptive damper in the MATLAB software. In 2010, Salem and colleagues [7], compared an active suspension system to the fuzzy control and the PID controller. In 2010, Cao and colleagues [8], proposed a development fuzzy logic controller for active suspension system. In 2010, Shirdel [9], designed the Linear Quadratic regulator controller (LQR) controller and $H \rightarrow \infty$ controller for active suspension in the linear quarter car model. In 2010, Tabatabai [10], designed a fuzzy PID controller for nonlinear active suspension system. In 2008, Coa and colleagues [11], proposed a new fuzzy logic controller for nonlinear active suspension system. In 2008, Sun and colleagues [12], reduced the vibration of vehicle by using a combination of suspension system. In 2007, Frang Kuo [13], investigated the mathematical model of the active suspension system with fuzzy controller. In 2007, Khajavi and colleagues [14], compared the response of semi-active suspension system by using fuzzy control damper and passive suspension system. In 2007, Segla and colleagues [4], compared the performance of passive, semi-active and active suspension systems. In 2007, Kamar and colleagues [15], investigated the model of a quarter car active suspension system with linear PID controllers. In 2007, Abu Bakar [3], compared the response of active suspension system by LQR controller and passive suspension system. In 2006, Kumar [16], obtained the linear model of active suspension system by LQR controllers and irregular road inputs. In 2005, Verros and colleagues [17], studied input random vibration in the passive and semi-active suspension system for a quarter model of vehicle.

The ride comfort, handling and stability in vehicle design is extremely important. Therefore, it's necessary to control and decrease the vibration of road disturbance [18]. So that, many efforts have been done by the later researcher to improve this criteria. In this paper, by studying the previous research to design the traditional controller such as PID and LQR, and intelligent fuzzy controller, the fuzzy neural network controller is proposed by using Feedback error learning (FEL). The performance of this controller is extremely better than previous controller. This intelligent controller uses the output of conventional LQR control to learn the fuzzy neural network and optimize the suspension system. Meanwhile, the response of this controller is very well in the nonlinear active suspension system.

To evaluate the performance of vehicle in the road disturbance, the equation of the quarter model is determined in linear and nonlinear active suspension system. Therefore, PID and LQR controller is simulated in MATLAB software and these are compared to FEL controller. On other hand, the FEL controller force is obtained.

2. Mathematical model of suspension system

2.1. Linear suspension system

A quarter model of active suspension system is shown in Fig. 1 where m_s is sprung mass, m_{us} is unsprung mass, K_s is spring stiffness, K_t is tire stiffness, b_s is damper coefficient, f_s is controller force, x_s is body vertical displacement, x_{us} is tire vertical displacement and r is the input system of road profile [4, 5, 19].

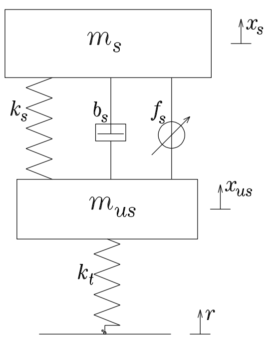

Fig. 1 Quarter model of active suspension system

To solve the system equations, the Lagrange method is used Eq. (1). By solving this equations, linear equations are obtained for active suspension system (Eqs. (2) and (3)):

$$\frac{D}{D_t}\left[\frac{\partial T}{\partial \dot{q}_i}\right]-\frac{\partial T}{\partial \dot{q}_i}+\frac{\partial U}{\partial q_i}=Q_i\,; \tag{1}$$

$$\begin{cases} m_s\ddot{x}_s+b_s\left(\dot{x}_s-\dot{x}_{us}\right)+k_s\left(x_s-x_{us}\right)-f_s=0;\\ m_{us}\ddot{x}_{us}+b_s\left(\dot{x}_{us}-\dot{x}_s\right)+k_s\left(x_{us}-x_s\right)+\\ \qquad +k_t\left(x_{us}-x_r\right)+f_s=0; \end{cases} \tag{2}$$

$$\begin{cases} \ddot{x}_s+\frac{1}{m_s}\left[b_s\left(\dot{x}_s-\dot{x}_{us}\right)+k_s\left(x_s-x_{us}\right)\right]=\frac{f_s}{m_s};\\ \ddot{x}_{us}+\frac{1}{m_{us}}\begin{bmatrix} b_s\left(\dot{x}_{us}-\dot{x}_s\right)+k_s\left(x_{us}-x_s\right)+\\ +k_t\left(x_{us}-x_r\right)\end{bmatrix}=\frac{-f_s}{m_{us}}. \end{cases} \tag{3}$$

2.2. Nonlinear model for suspension system

In this section, a quarter model for active suspension system is determined by nonlinear spring. Fig. 2 shows the displacement of the nonlinear spring where Δx is displacement and F_s is nonlinear spring force [20].

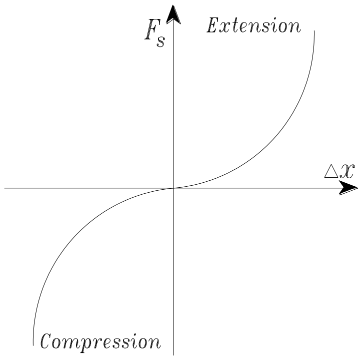

Fig. 2 Nonlinear spring

Also, F_s is determined by Eq. 4 where K_{ls} is the coefficient of linear stiffness spring and K_{ns} is the coefficient nonlinear stiffness spring:

$$F_s=k_{ls}\left(\Delta x\right)+k_{ns}\left(\Delta x\right)^3,\quad \Delta x=\left(x_s-x_{us}\right). \tag{4}$$

By solving the Lagrange equation, will be obtained the nonlinear equation for active suspension system (Eq. (5)):

$$\begin{cases} m_s\ddot{x}_s+b_s\left(\dot{x}_s-\dot{x}_{us}\right)+F_s-f_s=0;\\ m_{us}\ddot{x}_{us}+b_s\left(\dot{x}_{us}-\dot{x}_s\right)-F_s+k_t\left(x_{us}-x_r\right)+f_s=0. \end{cases} \tag{5}$$

2.3. Road profile

For determination of input profile, road disturbance is defined in Eq. (6) where $a = 0.02$ is the height of road profile:

$$x_r=\begin{cases} a\,cos\left(8\pi t\right) & 0.25\le t\le 0.75\\ 0 & \text{otherwise} \end{cases} \tag{6}$$

This profile is shown in Fig. 3 and is used for the simulation of the active suspension system in MATLAB software [21, 22].

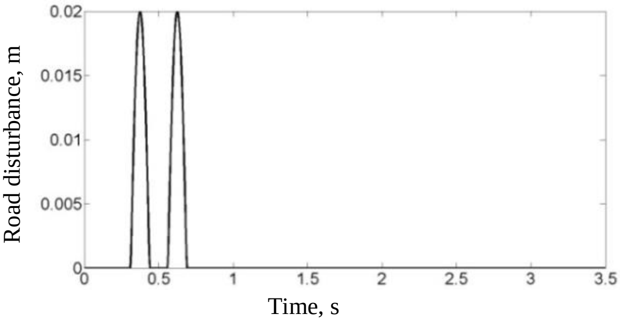

Fig. 3 Profile of road

In order to solve Eqs. (3) and (5), and to ensure that our controller design achieves the desired objective, our system is simulated with the following values [15]: m_s = 290 Kg, m_{us} = 60 Kg, $k_s = k_{ls}$ = 16800 N/m, k_{ns} = 168000 N/m^3, k_t = 190000 N/m, b_s = 1000 Ns/m.

2.4. Solving the motion equation

In the state space form, the suspension system is written as where $w(t)$ is road input and $u(t)$ is the control input (Eq. (7)) [23]:

$$\begin{cases} \dot{x}(t)=A\,x(t)+G\,w(t)+B\,u(t)\\ y(t)=C\,x(t)+D\,u(t) \end{cases} \tag{7}$$

By selecting the appropriate state variables, the matrix of the state space equations are determined by Eqs.(8) and (9).

$$A=\begin{bmatrix} \frac{-b_s}{m_s} & \frac{b_s}{m_s} & \frac{-k_s}{m_s} & \frac{k_s}{m_s}\\ \frac{b_s}{m_{us}} & \frac{-b_s}{m_{us}} & \frac{k_s}{m_{us}} & \frac{-\left(k_s+k_t\right)}{m_{us}}\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 \end{bmatrix}; \tag{8}$$

$$G=\begin{bmatrix} 0\\ \frac{k_t}{m_{us}}\\ 0\\ 0 \end{bmatrix};\quad B=\begin{bmatrix} \frac{1}{m_s}\\ \frac{-1}{m_{us}}\\ 0\\ 0 \end{bmatrix};\ D=0. \tag{9}$$

The nonlinear equations of suspension system in the state space method is not solved and these equations must be solved in the dynamic state.

3. Design of controllers

The schematic model of suspension system is shown in Fig. 4. In active suspension system, sensors are used to measure the acceleration of sprung mass and the signals from the sensor are sent to a controller. The controller is designed to take necessary actions to improve the performance abilities already set. Therefore, the control force is calculated and sent to actuator until reducing the road disturbance.

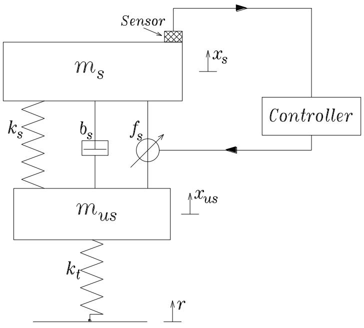

Fig. 4 Active suspension system

3.1. PID controller

PID Controller, including proportional gain K_p integral time constant T_i and derivative time constant T_d that is written as:

$$G_c(s) = K_P\left(1 + T_d S + \frac{1}{T_i S}\right) \tag{10}$$

Block diagram of PID controller for active suspension system is shown in Fig. 5.

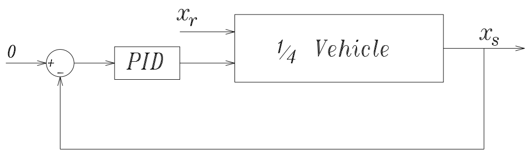

Fig. 5 Block diagram of active suspension system with PID controller

The Ziegler-Nichols tuning rules are used to determine the gains of PID controller [23]. These coefficients have shown in Table.

Table

Ziegler - Nichols tuning value

Controller	K_p	T_i	T_d
P	78500	∞	0
PI	70650	0.232	0
PID	94200	0.140	0.035

3.2. LQR controller

To design a state feedback controller, the gain of system K must determine. Block diagram of PID controller for active suspension system is shown in Fig. 6.

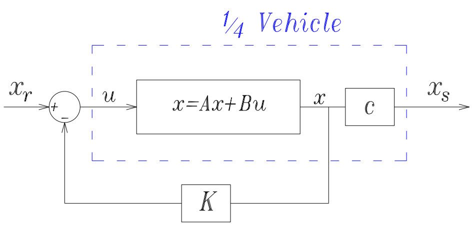

Fig. 6 Block diagram of active suspension system with LQR controller

3.3. Fuzzy neural network controller by using FEL

Traditional controllers is designed in the previous section, are used only for a special cases and are determined by the characteristics of the particular input. Thus, by changing the characteristics of inputs, this process must be repeated. For example, PID controller must be adjusted by Ziegler-Nichols rules and the gain of LQR controller must be computed so that these category can be extremely difficult. Therefore, a fuzzy neural network controller by using FEL is designed, so that the control coefficients can be determined in each cases. Also, the result of nonlinear system is extremely good. In addition, the performance of this controller is very well for complex system and can use the dynamic system, too. In this method, an intelligent fuzzy neural network controller is proposed to improve the output of system [24].

The strategy, consist of intelligent and conventional paths. i.e. The LQR controller is essential for guarantying global stability of the overall system and an intelligent feed forward controller is applied to improve quality of the control. Block diagram of this strategy is shown in Fig. 7. From this figure it is seen that the output of conventional controller (U_{lqr}) is used to learn the fuzzy neural network system. Also, FEL controller uses the input and derive from error to optimize the system.

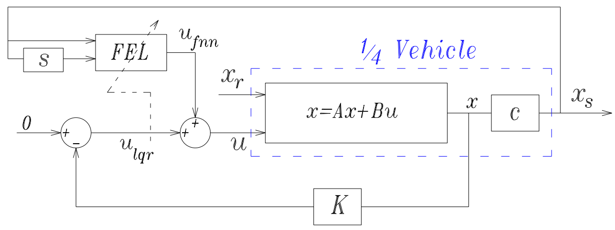

Fig. 7 Block diagram of proposed FEL

3.3.1. Improve the performance of FEL in the fuzzy neural network

The fuzzy neural network (FNN) processor advantages of both fuzzy logic (FL) and neural network (NN). It combines the capability of fuzzy reasoning in handling uncertain information and the capability of artificial neural networks in learning from the process. From the adaptive control overview, the FNNs have been used to control nonlinear and uncertain systems [24, 25]. A schematic diagram of the proposed FEL is shown in Fig. 8.

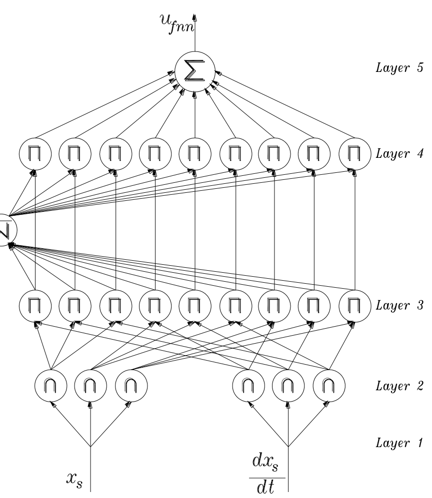

Fig. 8 Structure of proposed FEL

From Fig. 8 it is seen that the FEL consists of the 5 layers. Layer 1 accepts input variable. Layer 2 is used to calculate Gaussian membership values. The node in this layer represents the term of the respective linguistic variables. The node in layer 4 performs the normalization of firing strength from layer 3. The node in layer 4 performs the normalization of firing strength is helpful in improving the convergence performance of the linear adaptive process. Layer 5 is the output layer.

Eqs. (11)-(14) represent the formula that is used in the FEL structure.

The equation of layer 1 is:

$$o_i^1 = u_i^1 . \tag{11}$$

The equation of layer 3 is:

$$o_l^3 = \prod_i u_i^3 . \tag{12}$$

The equation of layer 4 is:

$$o_l^4 = \frac{u_l^4}{\sum_{l=1}^{9} u_l^4} . \tag{13}$$

The equation of layer 5 is:

$$u_{ff} = \sum_{l=1}^{9} u_l^5 \, w_l . \tag{14}$$

Also, o_i^k denotes the ith mode output in layer k and u_i^k denotes the i-th input of a node in the k-th layer.

3.3.1.2. Learning algorithm

The purpose of the training algorithm is to adjust the network weights through the minimization of the following cost function (Eq. (15)) [26]:

$$E = \frac{1}{2}\sum_{i=1}^{n} e_i^2 , \tag{15}$$

where

$$e = u_{lqr} = u - u_{fnn} . \tag{16}$$

So, u is the final control signal and u_{fnn} is the FEL output. In fact, it is describe that the output of CFC controller (u_{LQR}) reaches to zero. Therefore, the well-known BP algorithm is used in Eq. (17) where η is learning rate and w is tuning parameter. At the end, m_{ij}, δ_{ij}, w_l are adjusted.

$$W(k+1) = W(k) + \eta\left(-\frac{\partial E(k)}{\partial w(k)}\right) . \tag{17}$$

4. Results and discussion

4.1. Performance of linear suspension system

By solving the state space equations in the MATLAB software, the response of linear suspension system to road Profile is obtained. Then, the results are presented in Figs. 9-13.

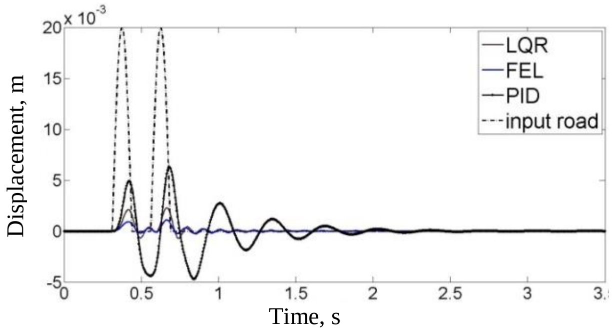

Fig. 9 Vertical body displacement by road profile

Fig. 9-10 represent the time response plot of vertical body displacement by PID, LQR and FEL controllers. From Fig. 10 it is seen that maximum vertical displacement of the vehicle in the PID, LQR and FEL controllers is 0.0063 m, 0.0018 m and 0.0011 m, respectively.

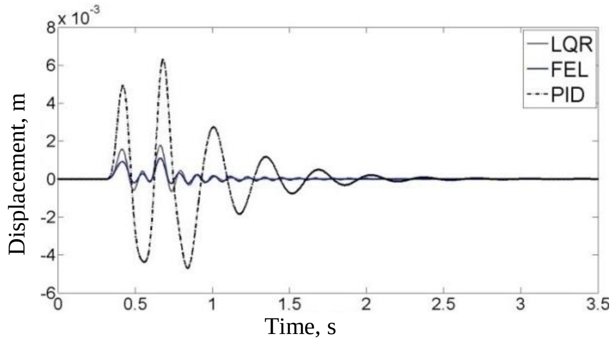

Fig. 10 Vertical body displacement in linear model

Fig. 11 represent the time response plot of vertical body velocity by PID, LQR and FEL controllers. From this figure it is seen that maximum vertical velocity of the vehicle in the PID, LQR and FEL controllers is 0.162, 0.045 and 0.027 m/s, respectively.

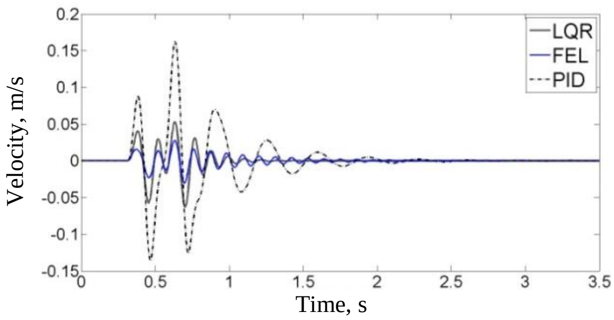

Fig. 11 Vertical body velocity in linear model

Because of ride comfort, handling and stability, vertical body acceleration is extremely important category in the vehicle.

In Fig. 12, the vertical body acceleration represent by PID, LQR and FEL controllers. From this figure it is seen that response of FEL controller is better than LQR. Figs. 10-12 illustrated displacement, velocity and acceleration of the sprung mass with this intelligent controller 38.9%, 40% and 46.3% decreased respect to LQR controller.

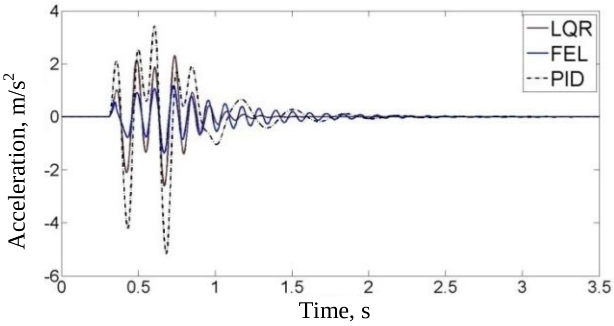

Fig. 12 Vertical body acceleration in linear model

The force of actuator by FEL controller is shown in Fig. 13. Therefore, the pressure of movement of piston in the actuator will obtained by this force. Meanwhile, the frequency response of this figure is about 7 Hz that it is appropriate for performance of actuator.

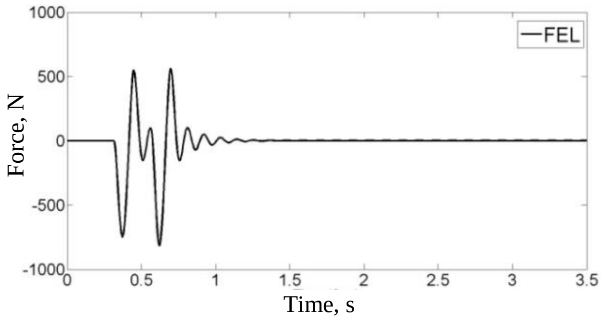

Fig.13 Force of controller by road profile

4.2. Performance of nonlinear suspension system

By solving the state space equations with dynamic method, is obtained the response of nonlinear suspension system to road Profile. Then, the results are presented in Figs. 14-18. Figs. 14-15 represent the time response plot of vertical body displacement by PID, LQR and FEL controllers. From Fig. 17 it is seen that maximum vertical displacement of the vehicle in the PID, LQR and FEL controllers is 0.0056, 0.00061 and 0.00028 m, respectively.

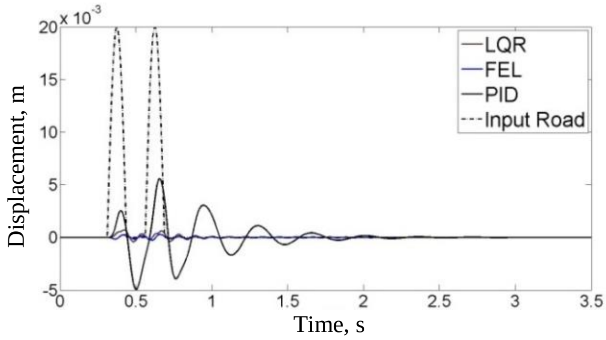

Fig. 14 Vertical body displacement by road prof

Fig. 15 represent the time response plot of vertical body velocity by PID, LQR and FEL controllers. From this figure it is seen that maximum vertical velocity of the vehicle in the PID, LQR and FEL controllers is 0.121, 0.023 and 0.018 m/s, respectively.

In Fig. 16, the vertical body acceleration represents by PID, LQR and FEL controllers. From this figure it is seen that the response of FEL controller is better than LQR. Figs. 15-17 illustrated displacement, velocity and acceleration of the sprung mass with this intelligent controller 66.6%, 21.7% and 25% decreased respect to LQR controller.

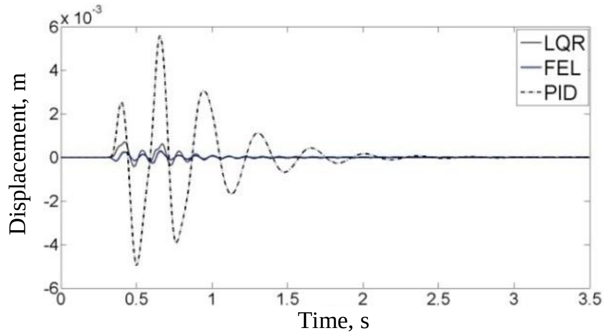

Fig. 15 Vertical body displacement in nonlinear model

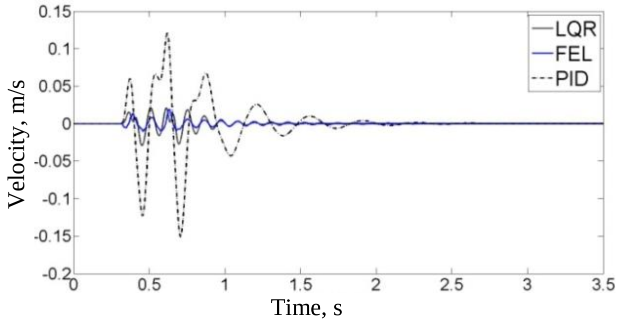

Fig. 16 Vertical body acceleration in nonlinear model

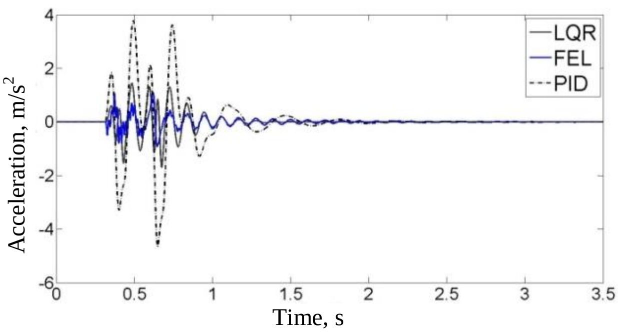

Fig. 17 Vertical body acceleration in nonlinear model

The force of actuator by FEL controller is shown in Fig. 18. Therefore, the pressure of movement of piston in the actuator will obtained by this force. Meanwhile, the frequency response of this figure is about 7 Hz that it is appropriate for performance of actuator.

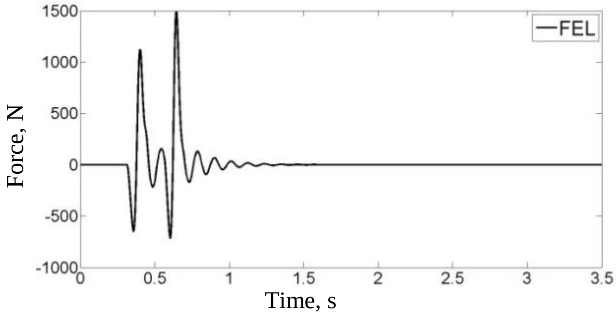

Fig. 18 Force of controller by road profile

5. Conclusion

Since, the determination of ride comfort, steering and stability in the vehicle is the criteria which with it human judges about the design and quality construction of the vehicle, this category is investigated by previous researcher. But, they used traditional controllers; such as PID and LQR, and intelligent fuzzy controller. In this paper, FEL controller is designed by combination of traditional LQR controller and intelligent FNN controller. the performance of active suspension system is improved by this controller and is decreased the vibration of road disturbance to passenger. Meanwhile, this controller is designed for linear and nonlinear model of active suspension system. Then, it is seen that this controller is the best in each condition. Also, in this study the code in MATLAB software is written and it is used for every active suspension system. At the end, the control force for linear and nonlinear system is obtained. The most important results of this paper are as follows:

1 - the performance of linear suspension system by LQR traditional controller is better than the PID traditional controller.

2 - The performance of PID controller is not suitable for the nonlinear model and it's better not to use it.

3 - In the linear model of active suspension system, displacement, velocity and acceleration of the sprung mass by FEL controller 38.9%, 40% and 46.3% decreased respect to LQR controller.

4 - In the linear model of active suspension system, displacement, velocity and acceleration of the sprung mass with this intelligent controller 66.6%, 21.7% and 25% decreased respect to LQR controller.

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AKTYVIOSIOS PAKABOS SISTEMOS SU VALDIKLIU FEL PROJEKTAVIMAS

R e z i u m ė

Kadangi virpesiai yra vienas svarbiausiu veiksnių, iš kurio žmonės sprendžia apie automobilio konstrukcijos kokybę, trikdžiai, sukelti kelio nelygumų, turi būti valdomi automobilio pakabos, kad užtikrintų važiavimo patogumą, vairavimo ir automobilio stabilumą. Tai leidžia pasiekti aktyvi pakabos konstrukcija. Šiame darbe projektuojamas neuroninio tinklo valdiklis FEL siekiant pagerinti aktyviosios pakabos sistemos pritaikomumą. Jis lyginamas su valdikliais PID ir LQR. Ketvirtis tiesinės ir netiesinės aktyviosios pakabos sistemos modelio modeliuojamas MATLAB įranga atsižvelgiant į kelio nelygumus, o kartu ir į aktuatoriaus valdomą jėgą, susijusią su šiais trikdžiais. Modeliavimo rezultatai rodo, kad tiesinės ir netiesinės pakabos su šiuo išmaniuoju valdikliu pakabintos masės įlinkis ir pagreitis yra atitinkamai 38,9 % ir 46,3 % bei 66,6% ir 25% mažesni negu pakabos su valdikliu LQR ir tai pagerina važiavimo patogumą, automobilio valdomumą ir stabilumą.

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IMPROVE ACTIVE SUSPENSION SYSTEM BY FEL CONTROLLER DESIGN

S u m m a r y

Since, the area of vibration is one the most important criteria which with it, human judges about the design and quality construction of the vehicle, the disturbances caused by road vibrations must be controlled in the vehicle suspension that ride comfort, steering and stability of the vehicle can be supplied. This is improved with active suspension system design. In this paper, fuzzy neural network controller by FEL is designed in order to improving applicability of the active suspension system and then its results is compared to conventional PID and LQR controller. Also, the quarter model of linear and nonlinear active suspension system is simulated in the MATLAB software with the road disturbance and an actuator control force which obtained by its disturbance.

Results of simulation illustrated that the deflection and acceleration of the sprung mass with this intelligent controller for linear model 38.9%, 46.3% and for nonlinear model 66.6%, 25% decreased respect to LQR controller and this category will be caused to increase more the ride comfort, steering and stability of the vehicle.

Keywords: active suspension system, LQR, PID controller, FEL controller, actuator.

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