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The Application of Fuzzy Logic Control Algorithm to Active Suspensions of Vehicles

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Abstract: In this paper, a fuzzy logic control design is presented for the control of an active suspension system. As a non-linear full vehicle model with seven degrees of freedom is adopted, the road roughness intensity is modeled as a filtered white noise stochastic process. Two cases of fuzzy logic control strategies are proposed. In the first case, one fuzzy controller is presented, the dynamic travel of suspension and the derivation of dynamic travel of suspension are designed as the input variables. In the second case, four controllers are designed, namely, the heave movement controller, the pitch movement controller, the roll movement controller and the logical controller. With the aid of software Matlab/Simulink, the simulation models of full vehicle model in two cases of controller are achieved. The time response of the vehicle model due to road disturbance is obtained for each control strategy. Simulation results demonstrate that the proposed active suspension system proves to be effective in the ride comfort and drive stability enhancement of the suspension system.

Keywords: Active suspension, Fuzzy logic control, Full vehicle model, Simulation

1 Introduction

The major purpose of suspension system is to provide passenger with ride comfort while maintaining the vehicle to be safe and stable .Passive suspension system can only offer a compromise between these two conflicting criteria by providing spring and damping coefficients with fixed rates. Active suspension control system can produce corresponding control force according to running status and road oscillations to maintain the suspension system to be the optimal status.

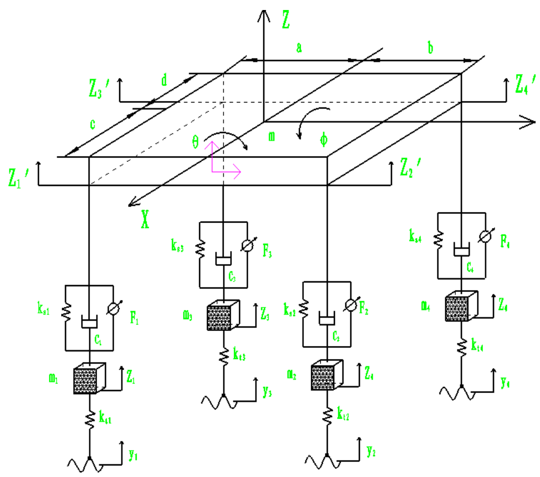
Suspension systems can not only contribute to the car's handling and braking for good active safety and driving pleasure, but also keep vehicle occupants comfortable and reasonably well isolated from road noise, bumps, and vibrations. The suspension also protects the vehicle itself and any cargo or luggage from damage and wear. The ride quality of a vehicle is significantly influenced by its suspension system, the road surface roughness, and the speed of vehicle. A vehicle designer can do little to improve road surface roughness, so designing a good suspension system with good vibration performance under different road conditions becomes a prevailing philosophy in the automobile industry. Passive suspension system can only offer a compromise between these two conflicting criteria by providing spring and damping coefficients with fixed rates. Active suspension control system can produce corresponding control force according to running status and road oscillations to maintain the suspension system to be the optimal status.

During the last decades, extensive studies concerning the semi-active and active suspension systems have been carried out. M. Bouazara [1] ,M.J. Richard and S. Rakheja Safety studied the comfort and safety of three dimentional model with optimal non-linear active seat suspension. Ikbal Eski [2]and Sahin Yildirim researched the robust neural network control of vehicle active suspension system. Rahmi Guclu [3] presented the fuzzy logic control of seat vibration of a non-linear full vehicle model. Crolla D.A. [4]studied the vehicle dynamics. A variety of research projects and publications deal with different types of active suspension systems have been discussed (E.C. Yeh & Y.J. Tsao, [5]) different vehicle dynamic models have been adopted according to different study purposes during research. A two degrees of freedom quarter body of vehicle suspension system model had been widely applied in vehicle suspension control research, it can indicate the vehicle body vertical movement ,but not include the pitch movement of the vehicle body. A four degrees of freedom half body of vehicle suspension system model can indicate the vehicle body vertical and pitch movement ,but not include the roll movement. A seven degrees of freedom full vehicle body of vehicle suspension system model can describe not only the vertical movement of the four wheels and the body center of gravity , but also the pitching and lateral movement, which makes it to be a relatively ideal model for suspension dynamic description. In our research, a seven degrees of freedom full vehicle body of vehicle suspension system model is established.

2 System Model

A schematic diagram of active suspension control system is shown in Fig.1.1, The half-body suspension system is represented as a seven degrees of freedom system.

The assumptions during the process of modeling are considered as following : (1) the vehicle body ,including the engine part is considered as a rigid body, which means the effect of engine is neglected. The vehicle consists of a single sprung mass connected to two four unsprung masses; (2) the axle and the tires connected are regarded as the unsprung mass, the contact manner of the center tire line and the road is point to point method;(3) the tires are modeled as simple linear springs without damping. For simplicity, all pitch angles are assumed to be small.



. Figure. 1.1.Model of seven degrees of freedoms

of suspension model

After applying a force- balance analysis to the model in Fig.1 the dynamics equation is governed by

$$m_i \ddot{z}_i = k_{ti}(y_i - z_i) + k_{si}(\dot{z}_i - z_i) + c_i(\dot{z}_i' - \dot{z}_i) + F_i, (i = 1,2,3,4)$$

$$m\ddot{z} = k_{s1}(z_1 - \dot{z}_1') + k_{s2}(z_2 - \dot{z}_2') + k_{s3}(z_3 - \dot{z}_3') + k_{s4}(z_4 - \dot{z}_4')$$

$$c_1(\dot{z}_1 - \dot{z}_1') + c_2(\dot{z}_2 - \dot{z}_2') + c_3(\dot{z}_3 - \dot{z}_3') + c_4(\dot{z}_4 - \dot{z}_4') - F_1 - F_2 - F_3 - F_4$$

$$J_y \ddot{\phi} = -[k_{s1}(z_1 - z_1') + c_1(\dot{z}_1 - \dot{z}_1') + k_{s3}(z_3 - z_3') + c_3(\dot{z}_3 - \dot{z}_3')]a + (F_1 + F_3)a$$

$$+[k_{s2}(z_2 - z_2') + c_2(\dot{z}_2 - \dot{z}_2') + k_{s4}(z_4 - z_4') + c_4(\dot{z}_4 - \dot{z}_4')]b - (F_2 + F_4)b$$

$$J_x \ddot{q} = -[k_{s3}(z_3 - z_3') + c_3(\dot{z}_3 - \dot{z}_3') + k_{s4}(z_4 - z_4') + c_4(\dot{z}_4 - \dot{z}_4')]c + (F_3 + F_4)c$$

$$+[k_{s1}(z_1 - z_1') + c_1(\dot{z}_1 - \dot{z}_1') + k_{s2}(z_2 - z_2') + c_2(\dot{z}_2 - \dot{z}_2')]d - (F_1 + F_2)d$$

; $\dot{z}_2 = z + b\phi + d\theta$; $\dot{z}_1 = z - a\phi + d\theta$

; $\dot{z}_4 = z + b\phi + c\theta$ $\dot{z}_3 = z - a\phi - c\theta$

The system state equation:

$$\dot{X} = AX + BQ$$

The system out equation:

$$\dot{X} = AX + BQ$$

The system state variables:

$$X = \begin{bmatrix} z_1 - \dot{z}_1 & z_2 - \dot{z}_2 & z_3 - \dot{z}_3 & z_4 - \dot{z}_4 & y_1 - z_1 & y_2 - z_2 & y_3 - z_3 & y_4 - z_4 & \dot{z}_1 & \dot{z}_2 & \dot{z}_3 & \dot{z}_4 & \dot{z} & \dot{\theta} & \dot{\phi} \end{bmatrix}^T$$

The system output variables：

$$Y = \begin{bmatrix} \ddot{z} & \ddot{\theta} & \ddot{\phi} & z_1 - z_1' & z_2 - z_2' & z_3 - z_3' & z_4 - z_4' & y_1 - z_1 & y_2 - z_2 & y_3 - z_3 & y_4 - z_4 \end{bmatrix}^T$$

The road irregularity formula is defined as

$$\dot{x} = -2p f_0 x + 2p\sqrt{G_0 v}w(t)$$

Using Grade B road surface, which is the common road ,gives the irregular road coefficients as $G_0 = 64 \times 10^{-6}$ m^2/m^{-1} and velocity v is $20 m/s$.

3 Controller System Design

The fuzzy logic control is one of the most attractive parts where fuzzy theory can be effectively applied. The fuzzy logic translates the mathematical control strategy into the linguistic control strategy. The fuzzy logic controller is usually based on the operator's knowledge, fuzzy modeling of the operator's control actions and fuzzy modeling of the process.

Two cases of fuzzy logic control strategies are proposed in the paper. In the first case, one fuzzy controller is presented, the aim of the fuzzy logic control system for the vehicle system uses the errors (e) in the dynamic travel of suspension and their derivatives as the input variables while the control force (F) are their outputs. In the second case, four controller , the heave movement controller, the pitch movement controller, the roll movement controller and the logical controller are designed.

3.1 method one

The fuzzy logic controller consists of three steps. The first step is the fuzzification, the second step is the reasoning using the fuzzy rule base, the last step is the defuzzification.

Fig. 2.1shows the block diagram of the suspension travel of the vehicle body. The error block is the difference between the actual suspension travel and the reference suspension travel.

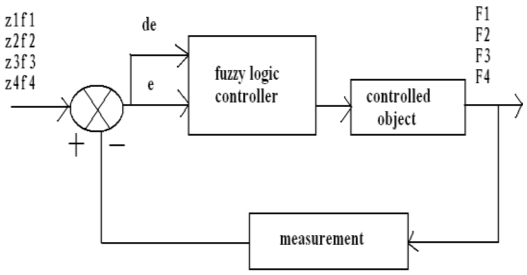


Figure 2.1 Block diagram of the acceleration control system

The first step in making a fuzzy logic controller is to take the inputs and determine the degree to which the inputs belong to each of the appropriate fuzzy sets via fuzzy membership function.

In the paper, a trial and error approach with the gaussian membership functions is used to achieve a good controller performance. It has seven grades; negative big (NB), negative medium (NM) ,negative small (NS) ,zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).

The defuzzification using centroid method is used and the defuzzification outputs are the controlled force.

Fig.2.2 indicates the special distribution of the fuzzy rule.

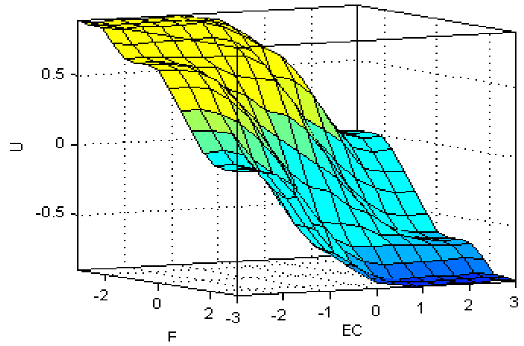


Figure 2.2 the special distribution of the fuzzy rule.

3.2 method two

In the second case, four controller , the vertical movement controller, the longitudinal movement controller, the lateral movement controller and the logical controller are designed. The schematic of the control system is showed in Fig.2.3. The vertical movement controller uses the errors in the vehicle body velocity and their derivatives as the input variables while the middle variables are the outputs. The longitudinal movement controller uses the errors in the vehicle body pitch angular motion and their derivatives as the input variables while the middle variables are the outputs. The longitudinal movement controller uses the errors in the vehicle body roll angular movement and their derivatives as the input variables while the control force are the outputs.

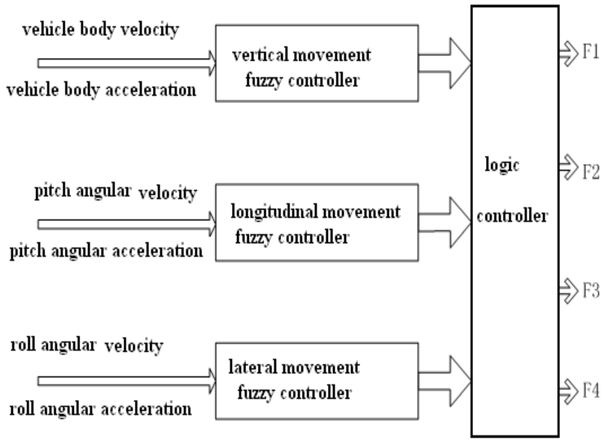


Figure 2.3 the schematic of control system

(1)vertical movement fuzzy controller

The basic scope for the vehicle body velocity ranges from -3 to 3, The basic scope for the vehicle body acceleration ranges from -3 to 3,

The basic scope for the middle variables ranges from -12000 to 12000, The quantification factor and scale factor is 1/3, 1/3 and 12000,respectively.

The Mamdani fuzzy logic type is used. A total of seven grades are designed for the vehicle velocity, vehicle acceleration and the middle variables in the paper: negative big(NB),negative medium (NM), negative small (NS),zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).

A trial and error approach with gaussian membership functions is selected to achieve a good controller performance. The centroid method is used in defuzzufication. Figure 2.4 indicates the special distribution of the fuzzy rule.

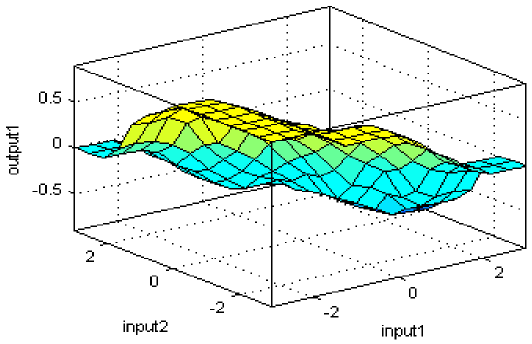


Fig.2.4 the special distribution of the fuzzy rule.

(2) longitudinal movement fuzzy controller

The basic scope for the vehicle body pitch angular velocity ranges from -3 to 3, The basic scope for the vehicle body pitch angular acceleration ranges from -3 to 3,

The quantification factor and scale factor is 1/3, 1/3 and 12000,respectively.

The Mamdani fuzzy logic type is used. for the longitudinal movement, suppose the vehicle is symmetrical to axle x, then $F_1 = F_3, F_2 = F_4$. A total of seven grades are designed for the vehicle pitch angular velocity, vehicle pitch angular acceleration and the middle variables in the paper: negative big(NB),negative medium (NM), negative small (NS),zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).The fuzzy rule table is shown in Table 1 ,which is developed based on these if-then rules .

Table 1 rule base for the longitudinal movement fuzzy logic controller

u		ec						
		U_f/U_b	NB	NM	NS	ZE	PS	PM	PB
e	NB	U_f	NB	NB	NM	NM	NS	NS	ZO
		U_b	PB	PM	PM	PS	PS	ZO	ZO
	NM	U_f	NB	NB	NM	NM	NS	NS	ZO
		U_b	PB	PM	PS	PS	ZO	ZO	ZO
	NS	U_f	NM	NM	NS	NS	ZO	ZO	PS
		U_b	PM	PS	PS	ZO	ZO	NS	NS
	ZE	U_f	NM	NS	NS	ZO	ZO	PS	PS
		U_b	PM	PS	ZO	ZO	NS	NS	NM
	PS	U_f	NS	ZO	ZO	PS	PS	PM	PM
		U_b	PS	PS	ZO	ZO	NS	NS	NM
	P	U_f	ZO	PS	PS	PM	PM	PB	PB

	M	U_b	ZO	ZO	ZO	NS	NS	NM	NM
	P	U_f	ZO	PS	PS	PM	PM	PB	PB
	B	U_b	ZO	ZO	NS	NS	NM	NM	NB

A trial and error approach with gaussian membership functions is selected to achieve a good controller performance. The centroid method is used in defuzzufication. Figure 2.5 indicates the special distribution of the fuzzy rule.

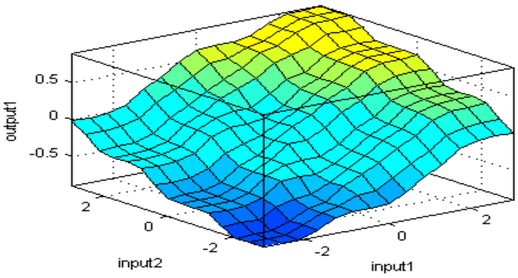


Fig. 2.5 the special distribution of the fuzzy rule.

(3) lateral movement fuzzy controller

The basic scope for the vehicle body roll angular velocity ranges from -3 to 3, The basic scope for the vehicle body roll angular acceleration ranges from -3 to 3,

The quantification factor and scale factor is 1/3, 1/3 and 12000,respectively.

The Mamdani fuzzy logic type is used. for the lateral movement, suppose the vehicle is symmetrical to axle y, then $F_1 = F_3, F_2 = F_4$.T

A total of seven grades are designed for the vehicle roll angular velocity, vehicle roll angular acceleration and the middle variables in the paper: negative big(NB),negative medium (NM), negative small (NS),zero (ZE), positive small (PS), positive medium (PM), and positive big (PB).The fuzzy rule table is shown in Table 3 is developed based on these if-then rules .for the lateral movement, suppose the vehicle is symmetrical to axle y, then $F_1 = F_2, F_3 = F_4$. The fuzzy rule table is shown in

Table2 rule base for the lateral movement fuzzy logic controller

u		Ec							
		U_l / U_r	NB	NM	NS	ZE	PS	PM	PB
	NB	U_r	NB	NB	NM	NM	NS	NS	ZO
		U_l	PB	PM	PM	PS	PS	ZO	ZO
	NM	U_r	NB	NB	NM	NM	NS	NS	ZO
		U_l	PB	PM	PS	PS	ZO	ZO	ZO
	NS	U_r	NM	NM	NS	NS	ZO	ZO	PS
e		U_l	PM	PS	PS	ZO	ZO	NS	NS
	ZE	U_r	NM	NS	NS	ZO	ZO	PS	PS
		U_l	PM	PS	ZO	ZO	NS	NS	NM
	PS	U_r	NS	ZO	ZO	PS	PS	PM	PM
		U_l	PS	PS	ZO	ZO	NS	NS	NM
	PM	U_r	ZO	PS	PS	PM	PM	PB	PB

	PB	U_l	ZO	ZO	ZO	NS	NS	NM	NM
		U_r	ZO	PS	PS	PM	PM	PB	PB
		U_l	ZO	ZO	NS	NS	NM	NM	NB

A trial and error approach with gaussian membership functions is selected to achieve a good controller performance. The centroid method is used in defuzzufication. Figure 2.6 indicates the special distribution of the fuzzy rule.

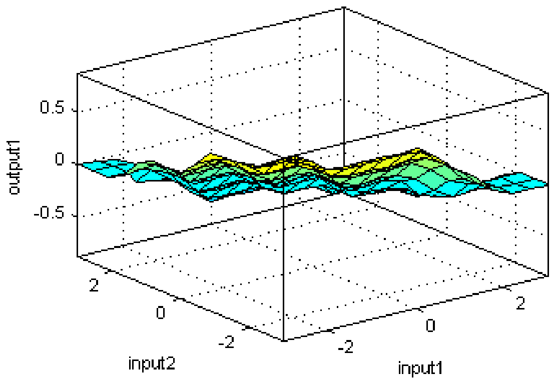


Fig. 2.6 the special distribution of the fuzzy rule.

3.2 logic controller

The input variable of logic controller is the middle variable of fuzzy logic controller, the output variables of the logic controller are the control force ,F1,F2,F3,and F4. a and b is the distance from the axle to the center of gravity of the vehicle body. C and d is the distance of front and right unsprung mass to the center of gravity of the axle. The vibration of the vehicle body can be regarded as the combination of translational movement of heave motion and the rotational movement surrounded to the centroid of the vehicle. The synthetic force is shown in Figure 2.7.

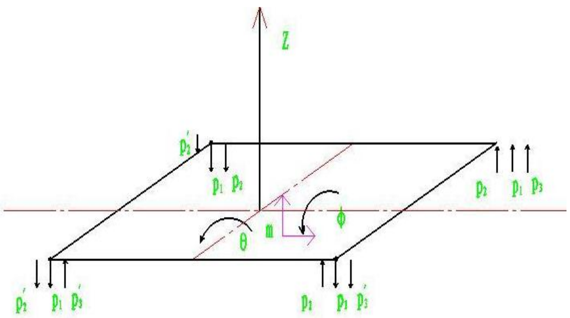


Fig.2.7 the effect of synthetic force

The output control force after logic controller is presented as followings:

$$F_1 = P_1 + P_2' - P_3'; \qquad F_2 = P_1 - P_2 - P_3$$

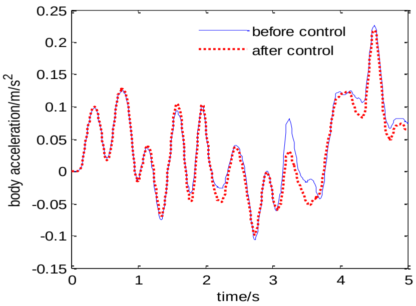
$$F_3 = P_1 + P_2' + P_3; \qquad F_4 = P_1 + P_3' - P_2$$

$$P_2.a = P_2'.b; \qquad P_3'c = P_3.d$$

4 Simulation

4.1 simulation of method one

The time responses of vehicle body vertical acceleration , vehicle body pitch angular acceleration, vehicle body roll angular acceleration, dynamic suspension travel of right rear suspension are shown from Figure 4.1 to Figure 4.4.



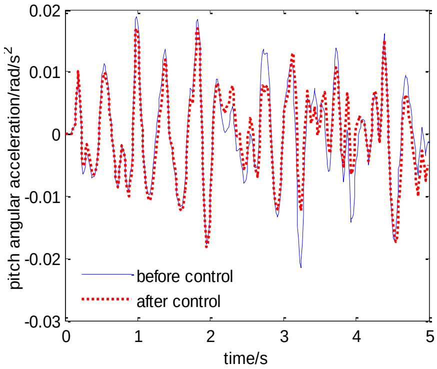
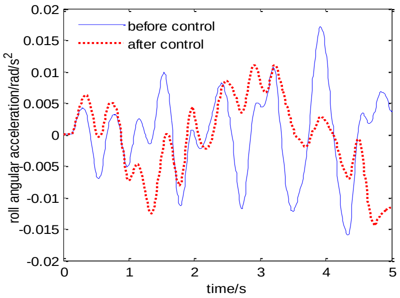


Fig.4.1 vehicle body vertical acceleration

Fig.4.2 vehicle body pitch acceleration



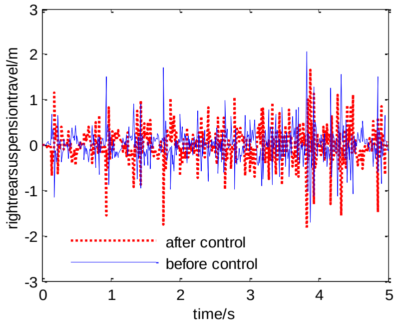
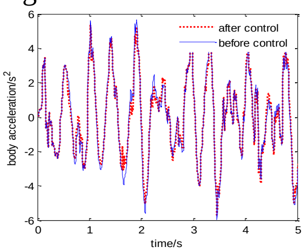


Fig.4.3 vehicle body roll acceleration

Fig.4.4 suspension travel of right rear suspension

4.2 simulation of method two

The time responses of vehicle body vertical acceleration , vehicle body pitch angular acceleration, vehicle body roll angular acceleration, dynamic suspension travel of left front suspension, dynamic suspension travel of right rear suspension , distortion of left front tire are shown from Fig.4.5 to Fig.4.10.



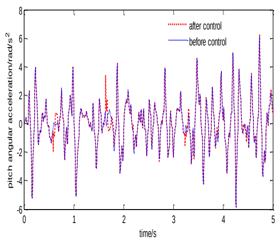
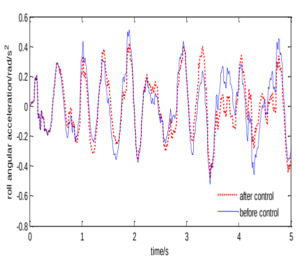


Fig.4.5 vehicle body vertical acceleration

Fig.4.6 vehicle body pitch acceleration



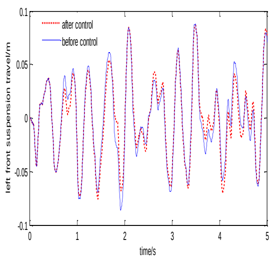
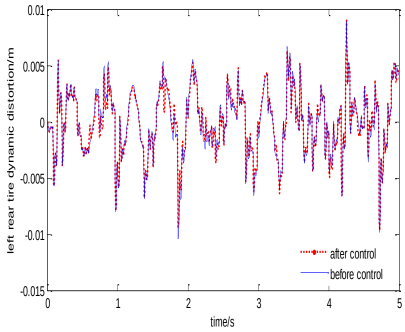


Fig.4.7 vehicle body roll acceleration

Fig.4.8 suspension travel of left front suspension



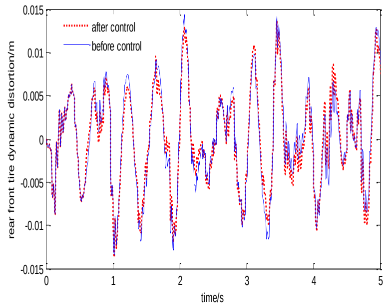


Fig.4.9 suspension travel of right rear suspension

Fig.4.10 distortion of left front tire

From the compare between two methods, performance melioration of body acceleration by method one is 9.3%, performance melioration by method two is 14.71%; performance melioration of pitching angular acceleration is 7.5% and 16.1%, respectively; performance melioration of rolling angular acceleration is 7.0%and 26.2% respectively; performance melioration of front suspension displacement is zero and 3.4%; and performance melioration of tire distortion is 5.3% and 4.8%.

5 Conclusion

In the paper, control system based on fuzzy logic algorithm for the whole vehicle active suspension system parameters has been designed. A non-linear full vehicle with seven degrees of freedom is presented which takes into account the heave, pitch and roll motions of the sprung mass and bounce motions of the unsprung masses. Two cases of fuzzy logic control strategies are studied. In the first case, one fuzzy controller is presented. In the second case, four controllers, those are the heave movement controller, the pitch movement controller, the roll movement controller and the logical controller, are obtained. With the aid of software Matlab/Simulink, the simulation models of full vehicle model in two cases of controller are achieved. The time responses of the vehicle model due to road disturbance and are obtained for each control strategy. Simulation results demonstrate that the proposed active suspension system proves to be effective in the ride comfort and driving stability enhancement of the suspension system. And from the comparison of two methods, controller two is more suitable than controller in performance melioration for the model.

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