Research on Fuzzy Logic Algorithm and Analogue Experiment on Active Suspension Control of Vehicle

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Abstract. A seven-degree of freedom whole body model with an active suspension system is described in the paper. First, construction of fuzzy control system is obtained. One fuzzy control discipline is designed. The fuzzy controller for vertical motion, fuzzy controller for pitch motion and roll motion is established. Second, controller for logical operation is designed, and the sketch of the composed fuzzy control system is presented. In addition, simulation analysis is obtained. The simulation results indicate that the ride comfort and the control stability is ameliorated by the proposed controller. Finally, simulation analogue of experiment is gained and the simulation environment of electronically controlled air suspension is constructed.

1. Introduction

The function of vehicle suspension is to bear the force between the car body and the wheel, complete the transfer of force and torque between the wheel and the car body, mitigate the impact load from the road to the car body, and reduce the vibration caused by impact load, to ensure the normal running of the vehicle. The ride comfort and handling stability of the vehicle is greatly determined by the suspension system of a vehicle, and the vibration reduction effect and other operational performance is affected by the suspension too. The contradiction between ride comfort and control stability is the problem of vehicle dynamics. The research on the control law of the suspension electronic control system has been widely concerned by scholars. The design and simulation analysis of the active and semi-active suspension system are conducted by many researchers.

One control method for the whole vehicle system model is presented in the paper. The fuzzy algorithm controller for vertical vibration, the fuzzy algorithm controller for pitch motion, and the fuzzy controller for vehicle body roll motion are designed respectively. The motion state of roll and pitch is different from that of vertical motion, and the fuzzy rules of roll and pitch are proposed according to the simulation model in this paper. At last, according to the motion of the vehicle, the logic operation controller of the three controllers was obtained, and the simulation software was used to conduct the modelling of the seven-degree-of-freedom vehicle system. Based on the simulation results, the fuzzy controller for the vehicle model is analysed and studied. At the same time, the simulation environment of electronically controlled air suspension is constructed.
2. Seven Degrees of Freedom Model for Vehicle System

The seven degrees of freedom model for vehicle system [2] is shown in figure 1. Differential equation of vehicle system is presented as:

\[
m_i \ddot{z}_i = k_{\theta} (y_i - z_i) + k_{zi} (\ddot{z}_i - z_i) + c_i (\dddot{z}_i - \ddot{z}_i) + F_i, (i = 1, 2, 3, 4)
\]

\[
\ddot{z}_i = z - a \phi + d \theta; \quad \ddot{z}_2 = z + b \phi + d \theta; \quad \ddot{z}_3 = z - a \phi - c \theta; \quad \ddot{z}_4 = z + b \phi + c \theta
\]

\[
m \ddot{z} = k_{zi} (z_i - z_1) + k_{z2} (z_2 - z_2) + k_{z3} (z_3 - z_3) + k_{z4} (z_4 - z_4)
\]

\[
c_i (\ddot{z}_i - \ddot{z}_i) + c_2 (\ddot{z}_2 - \ddot{z}_2) + c_3 (\ddot{z}_3 - \ddot{z}_3) + c_4 (\ddot{z}_4 - \ddot{z}_4) - F_1 - F_2 - F_3 - F_4
\]

\[
J_y \ddot{\phi} = -[k_{zi} (z_i - z_1) + c_1 (\ddot{z}_1 - \ddot{z}_1) + k_{z3} (z_3 - z_3) + c_3 (\ddot{z}_3 - \ddot{z}_3)]a + (F_1 + F_3) a \\
+ [k_{z2} (z_2 - z_2) + c_2 (\ddot{z}_2 - \ddot{z}_2) + k_{z4} (z_4 - z_4) + c_4 (\ddot{z}_4 - \ddot{z}_4)]b - (F_2 + F_4) b
\]

\[
J_x \ddot{q} = -[k_{z2} (z_2 - z_2) + c_2 (\ddot{z}_2 - \ddot{z}_2) + k_{z3} (z_3 - z_3) + c_3 (\ddot{z}_3 - \ddot{z}_3)]c + (F_3 + F_4) c \\
+ [k_{z1} (z_1 - z_1) + c_1 (\ddot{z}_1 - \ddot{z}_1) + k_{z4} (z_4 - z_4) + c_4 (\ddot{z}_4 - \ddot{z}_4)]d - (F_1 + F_2) d
\]

Where: \(a\)- the distance from the centre of mass of the car body to the axis of the front wheel (labelled with 1 and 3); \(b\)- distance from the centre of mass of the body to the axis of the rear wheels (labelled with 2 and 4); \(c\)- distance from the centre of mass of the car body to the axis of the right wheel (labelled with 3 and 4); \(d\)- the distance from the centre of mass of the car body to the axis of the left wheel(labelled with 1 and 2) \(j_x\)- the inertia of the vehicle body with respect to the X-axis; \(j_y\)- the inertia of the vehicle body with respect to the Y-axis; \(z_i (i = 1, 2, 3, 4)\)- vertical displacement of the mass of unspring; \(\ddot{z}_i (i = 1, 2, 3, 4)\)- vertical displacement at the four end points of the vehicle body; \(y_j (i = 1, 2, 3, 4)\)- excitation of the road.

**Figure 1.** Model of vehicle with seven degrees of freedom
3. Construction of Fuzzy Control System

According to different control objects, different control variables are adopted to control the seven-degree-of-freedom vehicle model [3,4]. Based on the simulation results, the effectiveness of the control method for the vehicle model is analysed in this paper. The fuzzy control system includes the fuzzy algorithm controller for vertical vibration, the fuzzy algorithm controller for pitch vibration, the fuzzy algorithm controller for control of roll motion, and the logic operation controller. In the vertical vibration controller, the speed and acceleration of the body are input variables. After the calculation of the vertical controller, the first intermediate output variable is obtained. In the pitch vibration controller, the angular velocity of the body pitch and the angular acceleration of the body pitch are taken as input variables. After the operation of the anti-nod controller, the second intermediate output variable is obtained. In the tilting vibration controller, the tilting angular velocity and tilting angular acceleration of the body are designed as input variables. After the calculation of the anti-tilting controller, the third intermediate output variable is obtained. Three intermediate output variables are taken as input variables for the logic operation controller and four output control forces are obtained after mathematical operation and logic operation.

3.1. Fuzzy Controller for Vertical Motion

The vehicle speed and acceleration are selected as input variables, and the first intermediate variable is designed as the output variable, in the fuzzy controller of vertical motion. In the design of the fuzzy system, according to the range of acceleration of the car body obtained by simulation, the fuzzy domain of the car body speed is set as [-2.5, 2.5], and the fuzzy domain of the car body acceleration is set as [-2.5, 2.5]. Seven fuzzy sets, NB, NM, NS, ZE, PS, PM, PB, are defined for vehicle speed. Seven fuzzy sets are defined for body acceleration: NB, NM, NS, ZE, PS, PM, PB; seven fuzzy sets are defined for intermediate variables: NB, NM, NS, ZE, PS, PM, PB. The membership function of gauss2mf is selected as the input and output membership function after repeated attempts. The fuzzy rules of vertical motion are shown in table 1.

| U | NB | NM | NS | ZE | PS | PM | PB |
|---|----|----|----|----|----|----|----|
| NB | PB | PB | PB | PB | PM | ZO | ZO |
| NM | PB | PB | PB | PB | PM | ZO | ZO |
| NS | PM | PM | PM | PM | ZO | NS | NS |
| E  | ZE | PM | PM | PS | ZO | NS | NM |
| PS | ZO | ZO | NM | NB | NB | NB | NB |
| PM | ZO | ZO | NM | NB | NB | NB | NB |

3.2. Fuzzy Controller for Pitch Motion and Fuzzy Controller for Roll Motion

In the design of fuzzy controller for pitch motion, the two variables of vehicle body pitch angle velocity and pitch angle acceleration are taken as the input variables, and the second intermediate variable is designed as the output variable. The fuzzy domain of pitch angle velocity is defined as [-2.5, 2.5], and the fuzzy domain of pitch angle acceleration is defined as [-2.5, 2.5]. Seven fuzzy sets, NB, NM, NS, ZE, PS, PM, PB, are defined for pitch angle velocity. Seven fuzzy sets of pitch angle acceleration are defined as: NB, NM, NS, ZE, PS, PM, PB. Seven fuzzy sets are defined for intermediate variables: NB, NM, NS, ZE, PS, PM, PB. The membership function of the input and output variables is selected gauss2mf function after repeated attempts. When pitching, set the car body right and left symmetry. After repeated experiments, the fuzzy rules of pitch motion are obtained. According to the same principle, the design of the controller for the roll motion takes the two variables of the body pitch Angle velocity and the body pitch Angle acceleration as the input and the third intermediate variable as the output variable. The fuzzy theory domain of roll velocity is defined as [-3, 3], and the basic theory domain of roll acceleration is [-3, 3]. Seven fuzzy sets are defined for the roll
velocity: NB, NM, NS, ZE, PS, PM, PB; roll acceleration is defined as: NB, NM, NS, ZE, PS, PM, PB. Seven fuzzy sets are defined for intermediate variables: NB, NM, NS, ZE, PS, PM, PB. The membership function of gauss2mf is selected as the input and output membership function after repeated attempts. When tilting, it is assumed that the car body is symmetrical to before and after, and the motion state of roll motion is different from that of pitch motion and vertical motion. After repeated tests, the fuzzy rules of vertical motion are shown in table 2.

Table 2. Rule for roll fuzzy control system

| U   | NB  | NM  | NS  | ZE  | PS  | PM  | PB  |
|-----|-----|-----|-----|-----|-----|-----|-----|
|     |     | NB  | NM  | NM  | NS  | NS  | ZO  |
|     |     | PB  | PM  | PM  | PS  | PS  | ZO  |
|     |     | NB  | NB  | NM  | NM  | NS  | NS  |
|     |     | PB  | PM  | PS  | PS  | ZO  | ZO  |
|     | NB  | NM  | NS  | NS  | ZO  | ZO  | PS  |
|     | PB  | PM  | ZO  | ZO  | NS  | ZO  | NS  |
|     | PS  | NS  | ZO  | ZO  | PS  | PS  | PM  |
|     | PM  | NS  | NS  | ZO  | ZO  | NS  | PS  |
|     | PB  | ZO  | PS  | PS  | PM  | PM  | PB  |
|     | PS  | ZO  | ZO  | ZO  | NS  | NS  | NM  |
|     | PM  | ZO  | PS  | PS  | PM  | PM  | PB  |
|     | PB  | ZO  | ZO  | NS  | NS  | NM  | NM  |

3.3. Controller for Logical Operation

In the design of the logic operation controller, three intermediate output variables of the fuzzy controller are taken as the input variables of the logic operation controller, and the output variable of the logic operation controller is the control force of the system. Parameter a represents the distance from the front axis to the centre of mass, and parameter b represents the distance from the rear axis to the centre of mass. Parameter c represents the distance from the mass of the left wheel of the vehicle to the centre of mass of the axle, and parameter d represents the distance from the mass of the right wheel of the vehicle to the centre of mass of the axle.

![Figure 2. The sketch of the composed system](image)
The overall vibration of the automobile body is regarded as the combined movement of the body in the vertical direction and the rotating motion around the body's centre of mass. The force exerted on the system after the integration is shown in figure 2. After the operation of the logic controller, the output is shown as

\[
F'_1 = P_1 + P_2' - P_3', \quad F'_2 = P_1 - P_2 - P_3 \\
F'_3 = P_1 + P_2' + P_3', \quad F'_4 = P_1 + P_3' - P_2 \\
P_2'a = P_2'b, \quad P_3'c = P_3'd
\]

4. Simulation Analysis
Simulation analysis shows that the road condition is b-class road and the speed is 30m/h. The results of the control strategy are shown in figure 3 to figure 6. The effects of the control strategy are shown in table 3. From the simulation results, the vehicle body vertical acceleration response of the body pitching angle acceleration response and body roll angle acceleration response are decreased, and tire dynamic deformation response are reduced, the effect of suspension stroke is slighted improved. The effect of the control method is shown in table 3.
Table 3. Effect of the controlled method

|                              | Performance improved of method two(%) |
|------------------------------|---------------------------------------|
| Body vertical acceleration   | 14.71                                 |
| Body vertical pitch acceleration | 16.1                               |
| Body vertical roll acceleration | 26.2                               |
| Dynamic travel of suspension  | 3.4                                   |
| Dynamic deformation of tire   | 4.8                                   |

5. Simulation Analogue of Experiment

The electronically controlled air suspension is simulated, and the control unit is shown in figure 7. The electronic control air suspension system is executed with ECU for overall control. ECU receives the electric signal detected by the sensor and sends instructions to the solenoid valve or stepper motor. Through the solenoid valve, the air spring is inflated and released, and the main and secondary air chamber opening and stiffness are controlled by the stepper motor. Due to the limited experimental conditions, the existing MC9SDP256MPVE and some peripheral equipment were used for simulation experiments. The experimental equipment is included as: MC9SDP256 development board was used to simulate and control solenoid valve through the control relay, and dc motor was used for the control of stepping motor. The overall structure of the simulation experiment principle is shown in figure 8.

6. Conclusion

The fuzzy controller for vertical movement, pitch movement and the roll movement is obtained respectively in the paper. The fuzzy controllers of different motions were established respectively, and the vertical acceleration of vehicle body was improved to 14.71% degree, the dynamic travel of suspension was improved to 3.4% degree, and the dynamic deformation of tire was improved to 4.8% degree. The comfort and control stability of the system were improved to some extent. Finally, the simulation environment of electronically controlled air suspension is constructed. The control program is programmed with language C and Codewarrior IDE is used to program, compile and download the programs online of the experiment.

7. Acknowledgments

Thanks for the found of NSFC (51505071) and the support of Northeastern University.

8. References

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