

Game Control of Multi-agent Damper System for Laterally Interconnected Air Suspension

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Abstract

To improve the performance of vehicles equipped with laterally interconnected air suspension (LIAS), a damper system is constructed based on multi-agent theory and Shapley value principle of cooperative game. The multi-agent control system consists of an information fusion agent, a ride comfort agent, a handling stability agent and a game coordination agent. The information fusion agent obtains vehicle status information from environment, and carries out the information transmission according to the requirements of other agents; on the basis of suspension dynamic deflection and its changing rate, the ride comfort agent indicates the intention of damping coefficients. The handling stability agent triggers the reasoning module according to the current interconnection state information, and indicates the intention of the damping coefficients by the vehicle roll angle, in which, the reasoning module is formed by the self-learning of fuzzy neural networks according to the damping coefficients optimized by genetic algorithm. The game coordination agent receives the intention of the damping coefficients from the above agents, then corrects the damping intention through the rules of cooperative game, and outputs the global optimum damping coefficients. Based on a bench test, a simulation model is established to perform the effectiveness of the multi-agent damper system proposed in this paper. The results have verified that the proposed multi-agent damper system not only improves ride comfort of vehicle with LIAS, but also restrains the roll motion of the vehicle body.

Key Words: Laterally Interconnected Air Suspension (LIAS), Multi-agent, Cooperative Game, Genetic Algorithm, Fuzzy Neural Network

1. Introduction

Air suspension is widely used in modern automobile because of its excellent vibration damping performance and so on. The interconnected air suspension using pneumatic pipeline to connect the adjacent air springs in the traditional air suspension has attracted more and more attention [1–4]. Researchers at home and abroad have studied its roll characteristics [5–7], pitch characteristics [8, 9], elimination twist characteristics [10,11], vibration isolation characteristics [12,13] and wheel load distribu-

tion [14,15]. Although the laterally interconnected structure makes the vibration isolation performance of the air suspension be improved, it will reduce the lateral stiffness of the air suspension. Therefore, the opening and closing control of the interconnected state needs to be made according to the different working conditions. But the damping control has not previously considered the change of the interconnection state, resulting in a decrease in its control effect. In order to improve the performance of the LIAS, the damping coefficients of the damper needs to be adjusted dynamically according to the change of the interconnection state. However, there are quite a few research findings about the control of LIAS damper sys-

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tem cooperating with the interconnection state. In 2014, Cui has designed the hierarchical control strategy to control the interconnection states and the damping coefficients of the dampers respectively [16]. In 2016, Ju has proposed the intimated skyhook control theory of laterally interconnected air suspension to control the opening and closing of interconnected states, so as to improve the ride comfort of the vehicle [17].

Currently, due to the inter-infiltration of biology, computer science, artificial intelligence, control science, sociology and other disciplines, multi-agent system as the latest development of artificial intelligence has attracted more and more attention from many scholars, and has become the focus of current control disciplines [18–22]. At the same time, as a theory of studying confliction and cooperation among intelligent agents, the cooperative game theory mainly studies the influence process of the behavior between agents and how the intelligent agents make their own decisions in the interaction [23]. Cooperative game theory can not only select the decision-making for the participants in the position of a decision maker, but also find the discipline of interaction between the two sides in the process of analysis and decision making. By this way, the problems can be solved in a more reasonable way. The combination of the two theories is not only widely used in traffic control, intelligent robot, automatic control, intelligent expert system and other fields [24], but also is a new way to research the intelligent control of damper system for LIAS.

At present, some scholars have proposed the methods of damping control. Among of them, the most typical method is the “Sky-hook” damping control strategy, but this method is not continuous, and requires dampers to have a wider frequency band. Otherwise, it is difficult to improve the performance of suspension [25]. Another commonly used method, the optimal control, only guarantees the desired performance of the ideal mathematical model, but ignores the nonlinearity of the suspension system and the existence of many uncertain factors [26]. Moreover, the traditional PID control algorithm is simple and convenient, but it has some limitations in solving the complicated and unstable problems [27]. And after the comprehensive analysis, the above methods have not taken the coordination of damping control and interconnected states into account, having poor matching ability

with the laterally interconnected structure. Therefore, these methods cannot fully reflect the good performance of the LIAS. In this paper, a multi-agent damper system for LIAS is constructed based on multi-agent theory, and all agents in this system are modeled. Firstly, information fusion agent is modeled based on a reactive agent model to achieve information publishing. Secondly, the ride comfort agent is modeled based on the “Belief-Desire-Intention” (BDI) agent model, and the fuzzy logic controller is designed to realize the matching from belief to intention. Thirdly, handling stability agent is modeled by the hybrid agent model. On this basis, genetic algorithm is used to optimize the damping of the vibration absorber, and combine fuzzy neural network technology to set up the controller. Finally, the controller of game coordination agent is constructed based on cooperative game theory, through the game of the control function index, coordinating the intention of each agent to ensure the functional allocation is reasonable, and then enhances the overall performance of the vehicle.

2. Vehicle Model with LIAS and Model Verification

2.1 Full Vehicle Model with Seven-degree of Freedom

For demonstrating the relationship between unsprung mass acceleration and road roughness coefficient in different vehicle speed, the entire system is modeled by the simplified linear pitch-plane seven-degree of freedom (7 DOFs) model. The 7 DOFs model comprises the vertical, roll and pitch movement of the body and vertical movement of four wheels. Furthermore, the model contains a physical model and a mathematical model. The physical model is shown as Figure 1.

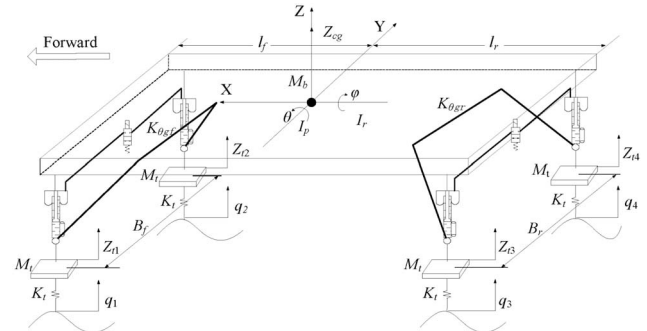


Figure 1. Physical model of vehicle body and wheels for vertical vibration.

where, Z_{cg} is the vertical displacement of the body centroid, m; l_f, l_r are distances from front and rear axles to the body centroid, m; M_b is the mass of the body, kg; M_t is the mass of each tire, m; I_r is the rotational inertia of the body around the X axis, $\text{kg}\cdot\text{m}^2$; I_p is the rotational inertia of the body around Y axis, $\text{kg}\cdot\text{m}^2$; ϕ is body roll angle, rad, which is assumed positive when the body rolls toward the right side; θ is body pitch angle, rad, which is assumed to be positive when the body bends forward; Z_{ii} ($i = 1, 2, 3, 4$) is vertical displacements of wheel, m; K_t is the vertical stiffness of each tire, kN/m; q_i is vertical displacement excitation of wheel, m; B_f, B_r are the distances between front and rear wheel tread respectively, m; $K_{\theta gf}$ is roll stiffness of front antiroll bar, N·m/deg; $K_{\theta gr}$ is roll stiffness of rear antiroll bar, N·m/deg.

The equation of motion of this linear vehicle mathematical model can be written as follows:

$$\begin{cases} M_b \ddot{Z}_{cg} = F_1 + F_2 + F_3 + F_4 - M_b \cdot g \\ I_r \ddot{\phi} = B_f(F_2 - F_1)/2 - B_r(F_4 - F_3)/2 \\ I_p \ddot{\theta} = (F_3 + F_4)l_r - (F_1 + F_2)l_f \\ M_t \ddot{Z}_{t1} = K_t(q_1 - Z_{t1}) - F_1 + M_b \cdot g \cdot l_r / (2(l_f + l_r)) \\ M_t \ddot{Z}_{t2} = K_t(q_2 - Z_{t2}) - F_2 + M_b \cdot g \cdot l_r / (2(l_f + l_r)) \\ M_t \ddot{Z}_{t3} = K_t(q_3 - Z_{t3}) - F_3 + M_b \cdot g \cdot l_f / (2(l_f + l_r)) \\ M_t \ddot{Z}_{t4} = K_t(q_4 - Z_{t4}) - F_4 + M_b \cdot g \cdot l_f / (2(l_f + l_r)) \end{cases} \quad (1)$$

In which,

$$\begin{cases} F_1 = (P_1 - P_a) \cdot A_{e1} + c_1 \cdot \dot{f}_{d1} - K_{\theta gf} \cdot (f_{d1} - f_{d2}) / B_f^2 \\ F_2 = (P_2 - P_a) \cdot A_{e2} + c_2 \cdot \dot{f}_{d2} + K_{\theta gf} \cdot (f_{d1} - f_{d2}) / B_f^2 \\ F_3 = (P_3 - P_a) \cdot A_{e3} + c_3 \cdot \dot{f}_{d3} - K_{\theta gr} \cdot (f_{d3} - f_{d4}) / B_r^2 \\ F_4 = (P_4 - P_a) \cdot A_{e4} + c_4 \cdot \dot{f}_{d4} + K_{\theta gr} \cdot (f_{d3} - f_{d4}) / B_r^2 \\ f_{d1} = Z_{t1} - (Z_b - l_f \theta + \phi \cdot B_f / 2) \\ f_{d2} = Z_{t2} - (Z_b - l_f \theta - \phi \cdot B_f / 2) \\ f_{d3} = Z_{t3} - (Z_b + l_r \theta + \phi \cdot B_r / 2) \\ f_{d4} = Z_{t4} - (Z_b + l_r \theta - \phi \cdot B_r / 2) \end{cases} \quad (2)$$

where, F_i ($i = 1, 2, 3, 4$) is suspension force, N; c_i ($i = 1, 2, 3, 4$) is damping of the suspensions; f_{di} ($i = 1, 2, 3, 4$) is suspension travel, m; A_{ei} ($i = 1, 2, 3, 4$) is effective areas of the air springs of front left, front right, rear left, rear right respectively, m^2 .

2.2 Air Spring and Interconnecting Pipe Model

The interconnected air springs can be considered as variable mass open insulation systems, and the motion of air in air spring under adiabatic condition can be express by the following equation:

$$P_i \left(\frac{V_i}{m_i} \right)^\kappa = P_{i0} \left(\frac{V_{i0}}{m_{i0}} \right)^\kappa = \text{const} \quad (3)$$

In which, m_{i0} ($i = 1, 2, 3, 4$) stands for the initial air mass in air spring i , kg; V_{i0} ($i = 1, 2, 3, 4$) stands for the initial volume of air spring i , m^3 ; P_i ($i = 1, 2, 3, 4$) is the absolute pressure in air spring i , Pa; P_{i0} ($i = 1, 2, 3, 4$) is the initial pressure in air spring i , Pa; m_i ($i = 1, 2, 3, 4$) stands for air mass in air spring i , m; V_i ($i = 1, 2, 3, 4$) stands for the volume of air spring i , m^3 ; κ is the isentropic exponent, and $\kappa = 1.4$.

For engineering applications, it is proper to simplify the throttling effect of pipe as orifice, expressed by the mass flow rate of air through orifice; the equation of mass flow rate through orifice under one-dimensional is entropic flow is as follow:

$$q_m = \begin{cases} A_i P_{up} \sqrt{\frac{1}{RT_{up}} \frac{2\kappa}{\kappa-1} \left[\left(\frac{P_{dn}}{P_{up}} \right)^{\frac{2}{\kappa}} - \left(\frac{P_{dn}}{P_{up}} \right)^{\frac{\kappa+1}{\kappa}} \right]} & \frac{P_{dn}}{P_{up}} \geq 0.528 \\ A_i P_{up} \left(\frac{2}{\kappa+1} \right)^{\frac{1}{\kappa-1}} \sqrt{\frac{1}{RT_{up}} \frac{2\kappa}{\kappa+1}} & \frac{P_{dn}}{P_{up}} < 0.528 \end{cases} \quad (4)$$

where, P_{up} is the pressure at upstream, Pa; P_{dn} is the pressure at downstream, Pa; T_{up} is the temperature at upstream, $^{\circ}\text{C}$; A_i is the effective circulation area of the orifice, m^2 .

Considering the throttling effect of the pipeline, the mass flow is hysteresis. Hysteresis effect of pipeline can be considered as a function of length and time:

$$\dot{m}(L, t) = \begin{cases} 0 & t \leq L/c \\ e^{-\frac{R_p RT_{dn} L}{2 P_{dn} c}} q_m \left(0, t - \frac{L}{c} \right) & t > L/c \end{cases} \quad (5)$$

where L is the interconnected pipe length, m; T_{up} is the terminal temperature of the interconnection pipe, $^{\circ}\text{C}$; R_t is the resistance coefficient of the interconnected pipe;

c is the speed of sound, m/s, which equals 346 m/s, at 25 °C.

2.3 Verification of Vehicle Model with 7 DOFs

In order to verify the effectiveness of the simulation model, the LIAS vehicle test platform was build based on the MTS-320 four-channel hydraulic servo oscillator, as shown in Figure 2. The prototype was refitted from a car chassis. The test car body was removed and replaced with a steel plate with multiple grooves. The grooves were used to place sandbags and test dummies, so as to flexibly configure the sprung mass. The test bench was equipped with 4 air pressure sensors of air springs, 4 air spring height sensors, and 8 acceleration sensors of sprung mass. Among them, 4 acceleration sensors were arranged at the connecting position between the axle and the wheels, so as to obtain the vertical acceleration at different positions of the sprung mass; the other were installed on the connecting position between the sprung mass and the suspensions to respectively obtain the vertical acceleration of the sprung mass at the positions of the front left, the front right, the rear left and the rear right suspension.

The effective area characteristics of the air spring used in the test were measured by the INSTRON 8800 single channel hydraulic servo vibration exciter. By the three order polynomial fitting, the effective area of air spring can be calculated by the following formula:

$$A = -1.6 \times 10^{-8} x^3 - 2.7 \times 10^{-7} x^2 - 3.5 \times 10^{-6} x + 9.1 \times 10^{-3} \quad (6)$$

where, x is the displacement of the air spring relative to the design height, m; A is the effective area of the air spring, m^2 .

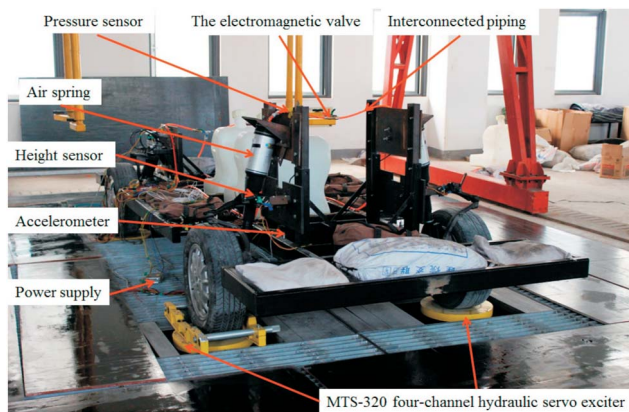


Figure 2. Test bench of LIAS system.

The 7 DOFs model is simulated under MATLAB/Simulink environment. Based on the equations above, a full car simulation model is built, and its parameters are set according to a test bench as Table 1.

Two-sided anti-phase sinusoidal travel excitation is used in validation; the amplitude is set to be 5 mm. As an example of the many correlation exercises, Figure 3 and Figure 4 show the responses of front left sprung mass acceleration and the roll angle of car body, in which the frequency is 1 Hz. Figure 3 shows that, the simulation result is in good agreement with the experiment result, which proves that the simulation model can accurately describe the vibration characteristics of the vehicle, and the main difference is that there are some small jumps in the experiment result. That is caused by the installation gap of the anti-roll bar in the front axle of the vehicle and the nonlinear characteristics of the plastic bush of the anti-roll bar. In the experiment, when the body roll was small, the anti-roll bar did not play a role, but when the body roll continued to increase, the gap between the anti-roll bar and the sprung mass was eliminated, and then the anti-roll bar began to play the role of body roll resistance. And the effect continued to increase, resulting that the left of the sprung mass acceleration performed as a small jump in experimental results. By the comparison of simulation and experiment results in Figure 4, curves of simulation and experiment show good agreement. These indicate that the simulation model is correct and can be used to research damping intelligent control.

Table 1. Parameters for full car model

Parameter	Value
Body mass M_b (kg)	1839
Wheel mass M_t (kg)	53.64
X axis rotational inertial I_r ($kg \cdot m^2$)	586
Y axis rotational inertial I_p ($kg \cdot m^2$)	3492
Front wheel tread B_f (m)	1.515
Rear wheel tread B_r (m)	1.515
Distance from centroid to rear axle a (m)	1.321
Distance from centroid to front axle b (m)	1.417
Tire stiffness K_t (kN/m)	206.2
Front stabilizer bar roll angle stiffness $K_{\phi_{gf}}$ (N·m/deg)	2400
Rear stabilizer bar roll angle stiffness $K_{\phi_{gr}}$ (N·m/deg)	1600
Air spring initial volume V_{i0} (m^3)	0.001026

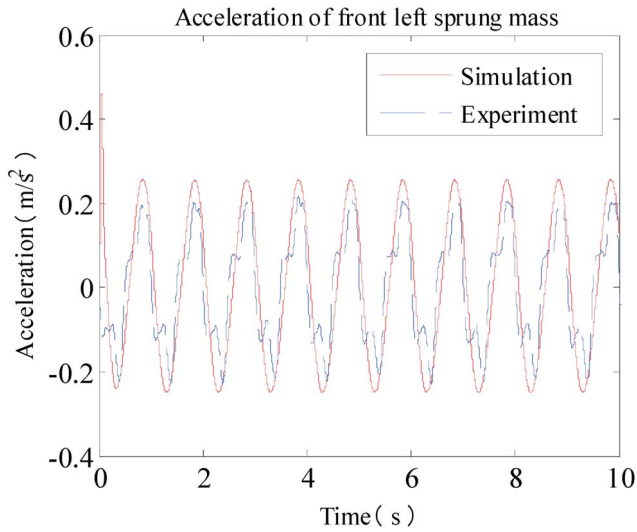


Figure 3. Acceleration of front left sprung mass.

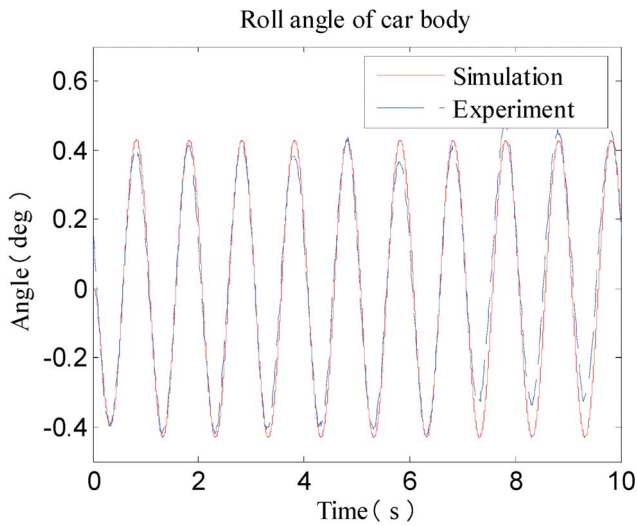


Figure 4. Roll angle of car body.

3. LIAS Multi-agent Damper System Architecture

Multi-agent system is a highly open intelligent system, which can solve the complex problems that cannot be solved by a single agent and it is considered as an effective way to solve the complex system problem.

In order to reduce the mass acceleration on the spring and to restrain the roll of the car body, the lateral interconnected suspension damper multi-agent system needs to make real-time perception and decisions for the different grades of road surface, interconnection state and body

condition. According to the functional requirements of multi-agent damper system for laterally interconnected suspension, the following multi-agent damper system is constructed. The structure is shown as Figure 5.

The multi-agent damper system for LIAS consists of an information fusion agent, a ride comfort agent, a handling stability agent and a game coordination agent. The structure from top to bottom is divided into information publishing layer, intelligent control layer and intention game layer. The information fusion agent in the information fusion layer collects the information of the environment and the information released by the agents in other layers, then integrates the information and selectively transmits them to the ride comfort agent, the handling stability agent and the game coordination agent; in the intelligent control layer, the ride comfort agent and the handling stability agent can read the relevant information from the information fusion agent, and transmit the optimal damping schemes to the game coordination agent based on their own function setting. According to the damping program from the ride comfort agent and the handling stability agent, and the information of sprung mass acceleration and body roll angle from the information fusion agent, the game coordination agent played a intention game, then, it developed a global optimum damping program, which realized the suppression of the sprung mass vibration and the adjustment of the car body roll.

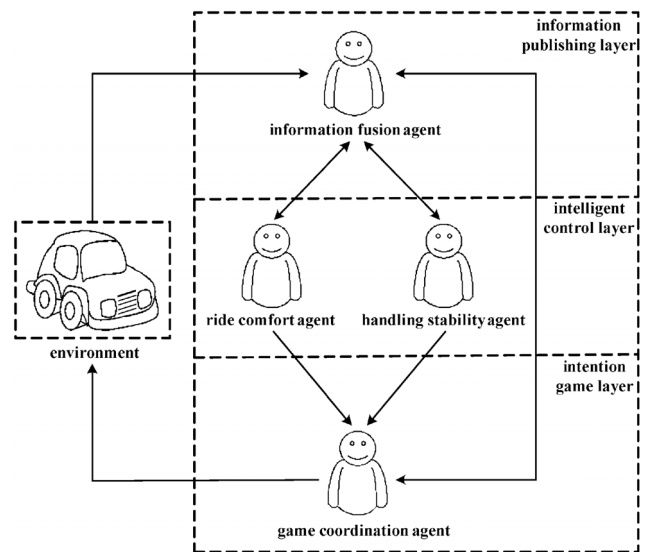


Figure 5. Multi-agent damper system for LIAS.

3.1 Design of Information Fusion Agent

As the function of the information fusion agent is simple, it only needs to collect information and sends information selectively according to the information requirements from the other agents; therefore, a reactive agent model that can monitor the environment is adopted. The model structure is shown as Figure 6.

Its behavior mainly has the following two points: one is to obtain the information of sprung mass acceleration, the suspension dynamic deflection and its rate of change information, body roll angle information, interconnection status information of front and rear interconnecting pipelines from the environment and the information requirements from the other agents; another is to trigger the information sorting according to the information requirement, then send the suspension dynamic deflection and its rate of change information to ride comfort agent, send the vehicle body roll angle information and the interconnection status information of the front and rear interconnecting pipelines to handling stability agent and send the sprung mass acceleration information and the vehicle body roll angle information to game coordination agent.

3.2 Project of Ride Comfort Agent

The ride comfort agent is one of the important components of the multi-agent damper system for LIAS and the undertaker to ensure the ride comfort. At the same time, its control target is to reduce the sprung mass acceleration.

As ride comfort agent needs to carry out the reasonable deduction according to the current working condition, for this reason, the ride comfort agent is modeled by the BDI agent model. Just as the name suggests, this model has three properties: belief, desire and intention. According to the functional requirements, the model of the ride comfort agent is shown as Figure 7.

(1) "Belief" contains dates describing the suspension dynamic deflection, $Belief_p = \{b_{pi}, \dot{b}_{pi}\}$, in which, b_{pi} is

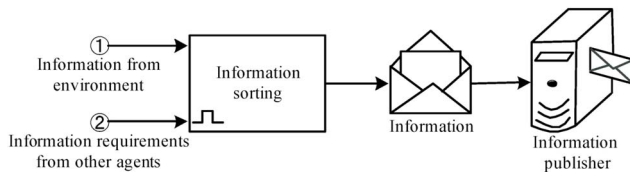


Figure 6. The model of information fusion agent.

suspension dynamic deflection of suspension, m ; $\dot{b}_{pi}$ is the derivative of b_{pi} , that is the change rate of each suspension dynamic deflection, m/s .

- (2) "Desire" is the control target for sprung mass vibration, that is, the minimum value of sprung mass acceleration under various operating conditions. This part of the data can be obtained by simulating the vehicle model under different operating conditions, and the goal also is also the requirements of the ride comfort.
- (3) "Intention" is the execution plans of four suspension damping in all kinds of working conditions, that is, $Intention_p = \{C_{pf1}, C_{pf2}, C_{pr1}, C_{pr2}\}$, in which, C_p means the damping coefficients of LIAS' output from LIAS' different place by ride comfort agent. $f1$ and $f2$ express the front air suspensions, and $r1$ and $r2$ express the rear air suspensions.
- (4) The fuzzy logic controller fuses the mapping relations between beliefs, desires, and intentions, and uses fuzzy inference rules to realize the matching of belief to intention, where fuzzy rules are in the form of "IF A and B Then C".

3.3 Project of Handling Stability Agent

In order to improve the operational stability of the vehicle, the handling stability agent obtains the roll angle information of the sprung mass from the environment, and reduces the roll angle of the sprung mass according to its own knowledge and decision-making ability. At the same time, it is necessary to deduce the implementation plans of the damping according to the roll state of the vehicle. Therefore, the handling stability agent is modeled by the hybrid agent model. This model is based on the BDI model, adding a fast trigger function, and the model's specific structure is shown as Figure 8.

(1) "Belief" contains dates describing the interconnec-

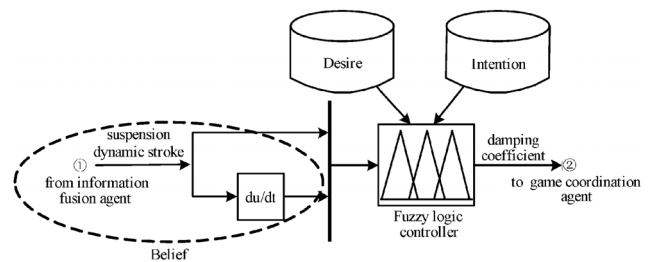


Figure 7. The model of ride comfort agent.

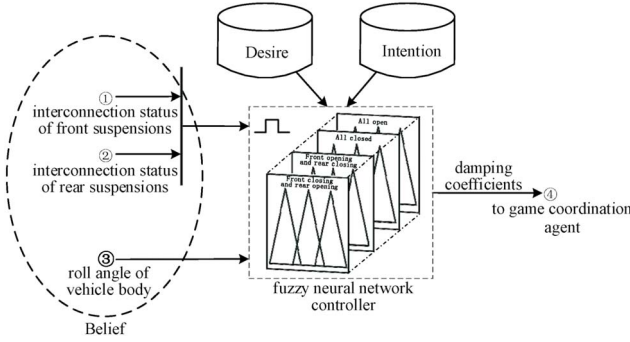


Figure 8. The model of the handling stability agent.

tion state of the front and rear air suspensions and roll characteristics, that is, $Belief_v = \{b_{vf}, b_{vr}, b_{roll}\}$, in which, b_{vf} and b_{vr} are the interconnection states from the front and rear air suspensions.

- (2) "Desire" is the control objective of car body roll, that is, the minimum value of the roll angle of sprung mass under various working conditions, which reflects the requirement of operation stability.
- (3) "Intention" is the execution plans of four suspension damping in all kinds of working conditions, that is, $Intention_v = \{C_{vf1}, C_{vf2}, C_{vr1}, C_{vr2}\}$, where, C_v means the damping coefficients of LIAS' output from LIAS' different place by handling stability agent.
- (4) The fuzzy neural network controller takes the damping parameters optimized by genetic algorithm as the output training samples, and uses the rudder angle of the vehicle as the input training sample to form the mapping rules of the belief to the intention. In which, the genetic algorithm is to optimize the damping of the suspension under different road surface and speed, and its fitness function is shown in equation (7):

$$\begin{cases}
 \text{objective function: } f(\theta) = \min(\theta) \\
 \text{design variables: } [c_{vf1}, c_{vf2}, c_{vr1}, c_{vr2}] \\
 \text{constraint conditions: } 0.2 \leq \xi \leq 0.4 \\
 f_{sws} \leq [f_d]/3 \\
 \frac{F_{DTL}}{(m_1 + m_2)g} \leq \frac{1}{3}
 \end{cases} \quad (7)$$

where, θ is the roll angle, rad; ξ is the damping ratio; f_{sws} is the root mean square value of the dynamic stroke of

suspension, m; F_{DTL} is the root mean square value of the tire dynamic load, N; f_d is the suspension limit stroke, m, $f_d = 0.08$ m; m_1 is the under spring mass, kg; m_2 is the sprung mass, kg.

3.4 Layout of Game Coordination Agent

Since the ride comfort agent and the handling stability agent only consider their own control performance, the damping programmes output by the two agents cannot make the sprung mass vibration and car body roll reach the best condition at the same time, therefore, from the point of view of game theory, the game coordination agent aims at coordinating the demands of the two agents for damping coefficients, and proposes a multi-agent game method based on the Shapley principle of cooperative game. That is, the weights of the damping coefficients for each agent are designed according to the average contribution of the ride comfort agent and the handling stability agent in alliance cooperation, by this way, a globally optimal damping intention scheme can be obtained. The model of the game coordination agent is shown as Figure 9.

- (1) "Belief" stores the demand for the damping factor of the ride comfort agent and the handling stability agent. That is, $Belief_g = \{C_{pf1}, C_{pf2}, C_{pr1}, C_{pr2}, C_{vf1}, C_{vf2}, C_{vr1}, C_{vr2}, \theta, \ddot{Z}\}$, in which, $\ddot{Z}$ is the sprung mass acceleration, m/s².
- (2) "Desire" is the global optimum state of the sprung mass vibration and the body roll angle through cooperative game:

$$f(x, y) = \min(\ddot{Z}, \theta) \quad (8)$$

- (3) "Intention" is the damping intention weight scheme

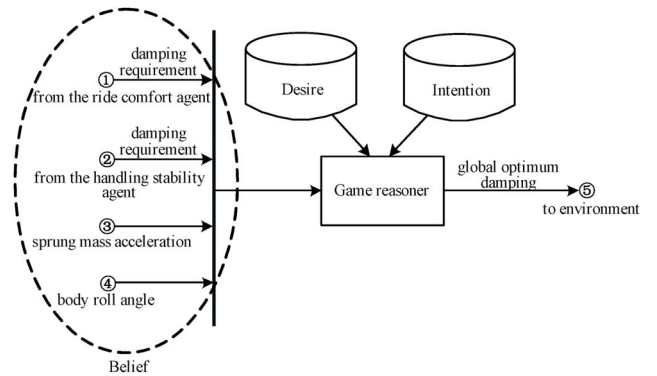


Figure 9. The model of game cooperation agent.

for the ride comfort agent and the handling stability agent, that is, $Intention_g = \{l_1, l_2\}$.

- (4) "Game reasoner" is designed based on the principle of Shapley value in cooperative game, and a real-time weight allocation scheme is obtained to determine the global optimum damping coefficient $\{C_{j1}, C_{j2}, C_{r1}, C_{r2}\}$ through constructing a performance index game matrix.

The following game matrix is constructed according to the cooperative game theory:

Using the sum of squares of the control function indicators to reflect the control effect:

J_1 is the functional index of the game for the ride comfort agent; the formula is as shown as equation (9)

$$J_1 = \int_{t_1}^{t_1+T} \ddot{z}^2(t) dt / \{\text{RMS}(\ddot{z}(t = t_1 \sim t_1 + T))\}^2 \quad (9)$$

where, RMS represents root mean square, that is, the square root of the average of squares of a set of numbers.

J_2 is the functional index of the handling stability agent involved in the game, and the formula is shown as formula (10):

$$J_2 = \int_{t_1}^{t_1+T} \theta^2(t) dt / \{\text{RMS}(\theta(t = t_1 \sim t_1 + T))\}^2 \quad (10)$$

The constructed game matrix is shown in equation (11):

$$M = \text{diag}(J_1, J_2) \quad (11)$$

The mathematical model based on the principle of Shapley value of cooperative game is:

$$\begin{cases} \text{objective function:} & J(M) = \min(L^T M L) \\ \text{design variables:} & L : [l_1, l_2] \\ \text{constraint conditions:} & I^T L = 1 \\ & L \geq 0 \end{cases} \quad (12)$$

where, L is the design variables, that is the weight coefficient, $L = (l_1, l_2)^T$; $I^T = (1, 1)$.

4. Simulation Results and Analysis

To verify the control effect of the proposed method,

the simulations of LIAS with multi-agent damper system and traditional damper system that refers to the damper system of LIAS proposed in document [16] are carried out under the mixed-working condition. Figure 10 shows the changes of the road excitation under the above mixed-working conditions for 30 seconds, in which, the time-domain signals during 0–10 seconds represent the changes of the road excitation at 80 km/h on class A road, the time-domain signals during 10–20 seconds represent the changes of the road excitation at 60 km/h on class B road and the time-domain signals during 20–30 seconds represent the changes of the road excitation at 50 km/h on class C road.

Therefore, according to the theory of random vibration, the performance changes of LIAS and the inhibiting effects of the body roll angle are expressed by sprung mass acceleration power spectral density and RMS values of sprung mass acceleration, suspension dynamic deflection and tire dynamic load [28], as shown in Figure 11–13 and Table 2–5.

Figure 11 shows the sprung mass acceleration of the LIAS with multi-agent damper system is smaller than the LIAS with traditional damper system and Figure 12 shows that, in 0–7 Hz, the power spectral density of sprung mass acceleration of the LIAS with multi-agent damper system is significantly smaller than the LIAS with traditional damper system and in 7–15 Hz, the power spectral density of sprung mass acceleration of the LIAS with multi-agent damper system is slightly smaller than the LIAS

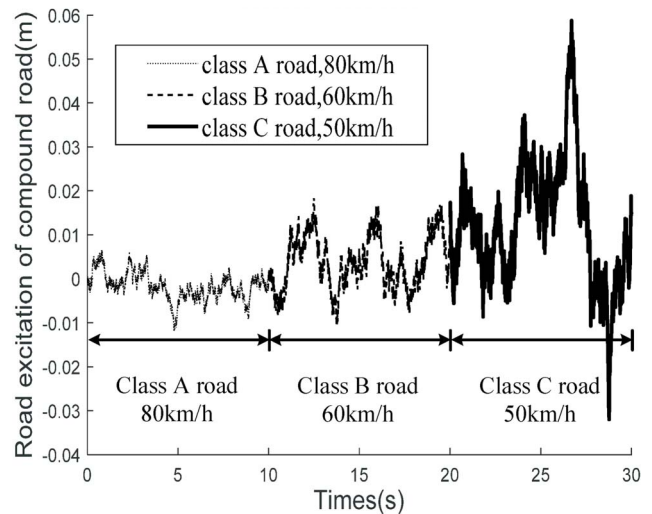


Figure 10. Time-domain signals of simulated random mixed-road excitation.

with traditional damper system. These indicate the multi-agent damper system is more effective in inhibiting vibration of sprung mass. Figure 13 shows the roll angle acceleration time history. The roll angle acceleration under the LIAS with multi-agent damper system is smaller, which indicates that the multi-agent damper system is more stable and effective.

According to Table 2–5, compared with the inter-

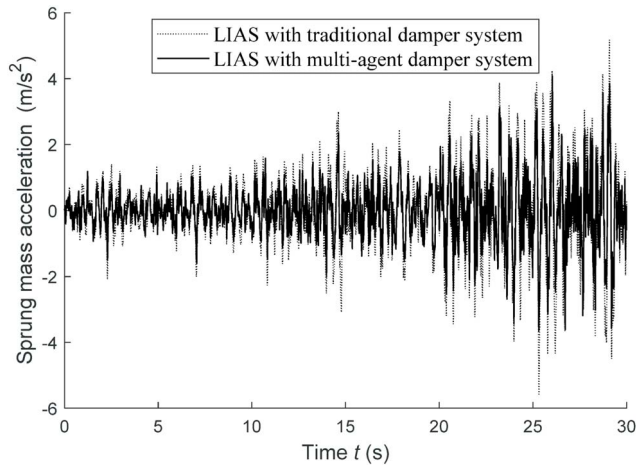


Figure 11. Sprung mass acceleration time history.

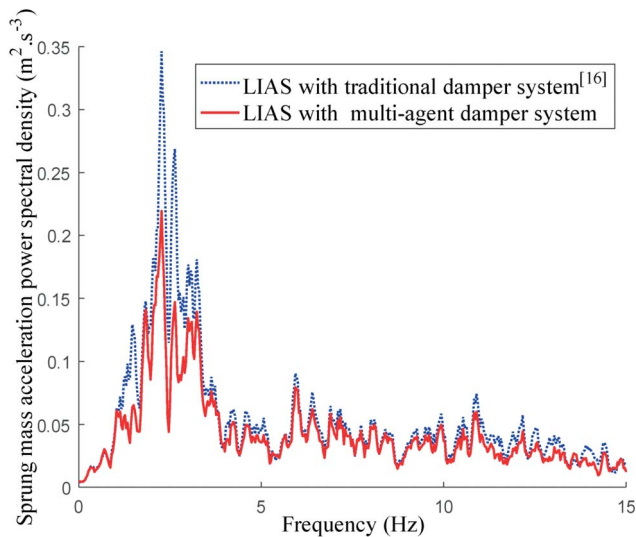


Figure 12. Sprung mass acceleration power spectral density.

connected air suspension with traditional damper system, the RMS value of sprung mass acceleration decreased by 14.95%; the RMS value of suspension dynamic deflection decreased by 10.64%; the RMS value of tire dynamic load increased by 3.08%; the RMS value of body roll angle decreased by 12.33%. The results show that the LIAS with multi-agent damper system can effectively reduce sprung mass acceleration and suspension dynamic deflection and has a good ride comfort and tire grounding; although the tire dynamic load increased slightly, but still satisfies the national standard and has little effect on the performance of the vehicle.

5. Conclusions

- (1) The multi-agent damper system model for the LIAS designed by multi-agent theory is correct, and the agents in the system can perceive the external environment information and make the correct decisions based on their respective design functions.
- (2) Simulation is carried out under the mixed-working condition to verify the control effect of the multi-agent damper system for the LIAS. Compared with the LIAS with traditional damper system, the LIAS

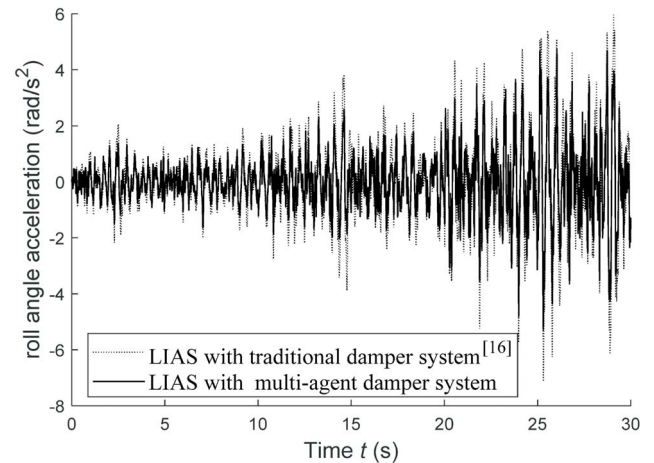


Figure 13. Roll angle acceleration time history.

Table 2. Comparison of RMS values of sprung mass acceleration

Performance index	RMS values of sprung mass acceleration (m/s^2)					
	Front left	Front right	Rear left	Rear right	Mean	Decline rate (%)
LIAS with traditional damper system [16]	1.2342	1.3030	1.2336	1.2999	1.2677	--
LIAS with multi-agent damper system	1.0136	1.1483	1.0067	1.1444	1.0782	14.95

Table 3. Comparison of RMS values of suspension dynamic deflection

Performance index	RMS values of suspension dynamic deflection (m)					
	Front left	Front right	Rear left	Rear right	Mean	Decline rate (%)
LIAS with traditional damper system [16]	0.0044	0.0048	0.0047	0.0050	0.0047	--
LIAS with multi-agent damper system	0.0039	0.0043	0.0041	0.0044	0.0042	10.64

Table 4. Comparison of RMS values of tire dynamic load

Performance index	RMS values of tire dynamic load (N)					
	Front left	Front right	Rear left	Rear right	Mean	Decline rate (%)
LIAS with traditional damper system [16]	435.6415	462.1056	426.6239	452.8497	444.3052	--
LIAS with multi-agent damper system	495.5217	413.1312	495.7862	427.4633	457.9756	-3.08

Table 5. Comparison of RMS values of body roll angle

Performance index	RMS values of body roll angle (°)		Decline rate (%)
	Front left	Front right	
LIAS with traditional damper system [16]		0.4185	--
LIAS with multi-agent damper system		0.3669	12.33

with multi-agent damper system shows a huge advantage: the RMS value of sprung mass acceleration decreased by 14.95%, the RMS value of suspension dynamic deflection decreased by 10.64%, and effectively suppress the body roll, the vehicle ride comfort and handling stability have been improved.

- (3) In the following study, the other control performance indexes of the vehicle will be involved in the game, so that the designed multi-agent damper system is more suitable for the actual driving conditions of vehicles.

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