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The Dynamics Simulation Analysis of Automotive Air Suspension and Control System Based on Adams and Matlab

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Abstract: This paper introduces the air suspension system, including its components and its characteristics, then the paper introduce the dynamics model of air suspension system. With the consideration that the air spring is nonlinear, that has great influence on the simulation accuracy, so the paper uses modeling and experiment to verify the nonlinearity of air spring. Then the paper introduces air Suspension control algorithm and air suspension hardware in the loop simulation, with detailed explanation of how to conduct the hardware in the loop simulation. Finally, the paper uses multi-body dynamics and finite element modal analysis technique based on Adams and Matlab to establish air suspension multi-body vehicle dynamics model, and makes road testing and simulation evaluation according to the national standards with focus on ride smoothness and natural frequency, the paper concludes that the accuracy and great application value of air suspension multi-body vehicle dynamics model. *Copyright © 2013 IFSA.*

Keywords: Air suspension, Air spring, Hardware in the loop simulation, Multi-body vehicle dynamics model.

1. Introduction

A vehicle equipped with air suspension system can obtain lower natural frequency, the variation of body vibration frequency would be very small in case of load change, and the vehicle height could stay the same [5]. The air suspension can effectively reduce the dynamic wheel load, thus the automotive could get good performance of comfort, but also obtain a high performance of handling stability, driving safety, with little the destruction to the road [6]. Air suspension has excellent controllability in the structure, it can easily regulate body height or automatically adjust suspension stiffness, damping, to accommodate different speeds and different roads, load changes. The air suspension can significantly improve riding smoothness and handling stability, so it has been widely used in advanced car, SUV, medium-sized car, senior car and heavy-duty truck [8].

There is a strong nonlinearity of rubber balloon , rubber bushing, shock absorber and other key components in the air suspension, so there is a complex issue "machine - electric - gas - liquid - control coupling" of suspension system [9]. From the existing technical documents, with constraints of analytical tools and technical conditions, when making air suspension vehicle dynamics analysis, the general treatment of air springs as a set of linear springs while ignoring the impact of height valve, connecting tubes, the auxiliary chamber and other parts, so the multi-body dynamics model of vehicle system could not reflect the true influences of nonlinear parameters on vehicle dynamics, thus it would lead to deviations of dynamics simulation analysis inevitably [13]. Due to the strong nonlinearity, being easily influenced by external disturbances, parameter change and other factors of air suspension system, the conventional control algorithm is difficult to meet the increasing requirements of ride comfort and steering stability and the control system is also more difficult to develop. Therefore, the establishment "dynamics and control dynamics model" which can reflect the nonlinear air spring is the key of developing air suspension [11].

Air suspension system mainly consists of air spring systems, guide system, shock absorbers, stabilizer bar, thrust rod, cushion stopper and other components. Vehicle air spring system includes air springs, auxiliary chamber, height valves, pressure valves, dust filter, accumulator, connecting pipes and so on [4]. The rubber balloon of air spring is made of rubber/ fabric structures, upper and bottom plate and the piston of air spring form a sealed space, which is full of compressed air to provide support reaction force, the air spring has a nonlinear characteristic. Automotive air suspension system is actually interacting air spring system [7].

1/2 vehicle dynamic model has four freedom degrees, namely a body movement, two axle vibrations and a pitch movement, 1/2 air suspension system dynamic model and the parameters of the vehicle as shown in Fig. 1.

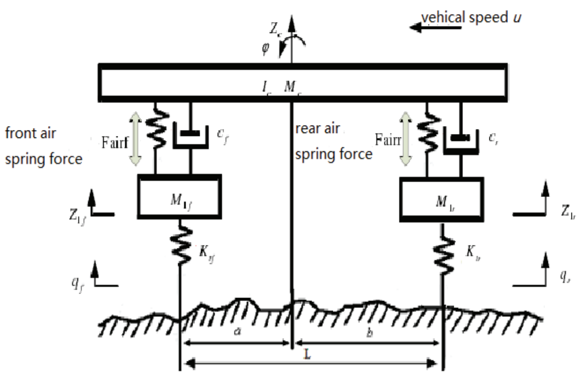


Fig. 1. Dynamic model of 1/2 air suspension system vehicle.

System dynamics equations show as follows:

$$M_2\ddot{z}_c + F_{airf} + C_f(\dot{z}_c - a\cdot\dot{\varphi} - \dot{z}_{1f}) + F_{air} = 0$$
$$M_2\rho_y^2\ddot{\varphi} - F_{air}\cdot a - C_f(\dot{z}_c - a\cdot\dot{\varphi} - \dot{z}_{1f})\cdot a + F_{airr}\cdot b = 0 \quad ,$$
$$M_{1f}\ddot{z}_{1f} + F_{airf} + C_f[\dot{z}_{1f} - (\dot{z}_c - a\cdot\dot{\varphi})] + K_{1f}(z_{1f} - q_f) = 0$$
$$M_{1r}\ddot{z}_{1r} + F_{airr} + c_r[\dot{z}_{1r} - (\dot{z}_c + b\cdot\dot{\varphi})] + K_{1r}(z_{1r} - q_r) = 0$$

where L is for wheelbase, a is for centroid distance of front axle and the body, b is for centroid distance of rear axle and the body, ρ_y^2 is for body inertia, M_{1f} is for front axle unspring mass, M_{1r} is for front axle unspring mass, M_c is for body mass, K_{1f} is for front tire stiffness, K_{1r} is for rear tire stiffness, F_{airf} is for front suspension air spring force, F_{airr} is for rear suspension air spring force, c_f is for front suspension system damping, c_r is for rear suspension system damping, z_c is for body vertical displacement at the centroid, z_{1f} is for body vertical displacement at the front axle, z_{1r} is for body vertical displacement at the rear axle, q_f is for input of front tires, q_r is for input of rear tires.

Air suspension has lower natural frequency when compared with the conventional leaf spring or coil spring suspension; the stiffness of air spring changes with the pneumatic pressure, the suspension load increases, the internal pressure of the airbag increases, the stiffness becomes larger, while the suspension load decreases, the internal pressure of the airbag decreases, the stiffness becomes smaller, the air spring is designed for equilibrium position, the natural frequency of the air suspension remained basically unchanged, and thus, a vehicle equipped with air suspension has excellent ride comfort performance; the air spring can be easily charge and emit gas, the height of air spring could stay unchanged while working load is changing, and could also be changed if needed to enhance the performance of suspension.

The dynamic characteristics of the air spring determine the vehicle's ride comfort and handling stability, its dynamic characteristics are air suspension matched main basis for selection. For testing the dynamic characteristics of the air spring, there are generally two methods, one is to get the static stiffness of air springs at different loads and different initial working heights through testing and get the dynamic character at the different excitation frequencies; another one is to calculate the dynamics of air spring at different pressure and initial forces on different heights and different excitation frequencies through the numerical method.

2. Dynamics Simulation of the Air Spring Considering Nonlinear Contact

2.1. The Study of Air Spring Characteristics Based on Experiment

In the paper, the SRI1R230a diaphragm air spring is selected as the object, and the U.S. MTS hydraulic servo system is selected as method to test its vertical elastic properties. The specific parameters of air springs are shown in Table 1.

Table1. Diaphragm air spring parameters.

Product Weight	8.3 kg	Assembly height (mm)	Load capacity		
Load capacity	1120~3280 kg		0.3 MPa	0.5 MPa	0.8 MPa
Working Pressure	0.3~0.8 MPa	415	620	1020	1620
Working stroke	250 mm	340	980	1610	2720
Recommended assembly Design height	275 mm	290	1020	1760	2800
Assembly pull Maximum height	425 mm	240	1470	1350	3700
Assembly compression Minimum height	175 mm	175	2300	3400	5200

The working principle of MTS hydraulic servo vibration test equipment and the test principle of air spring test are shown in Fig 2. MTS test system consists of three components: MTS dynamic test systems, data acquisition systems and MTS software control system. For the test sample, a target displacement signal is set through MTS dynamic test systems, then hydraulic servo system mechanism of dynamic test systems moves at a certain frequency.

The actual displacement signals would be sent to the data acquisition system through displacement sensor of dynamic test system and then after data processing through the MTS software control system by the data acquisition system through. With appropriate adjustment of the system parameters, the actual displacement signal and feedback displacement signal of the displacement sensor system is within the error range, the measured sample could be used in related tests.

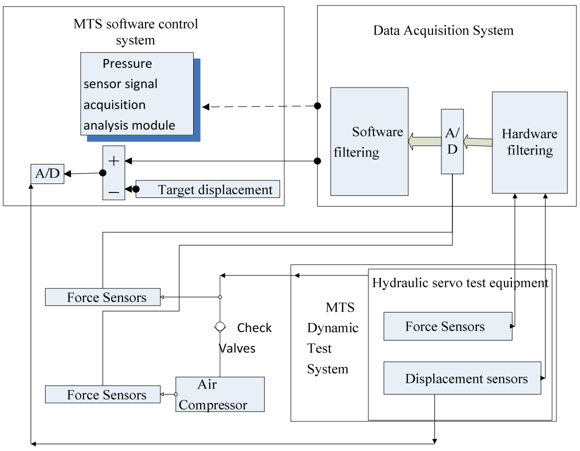


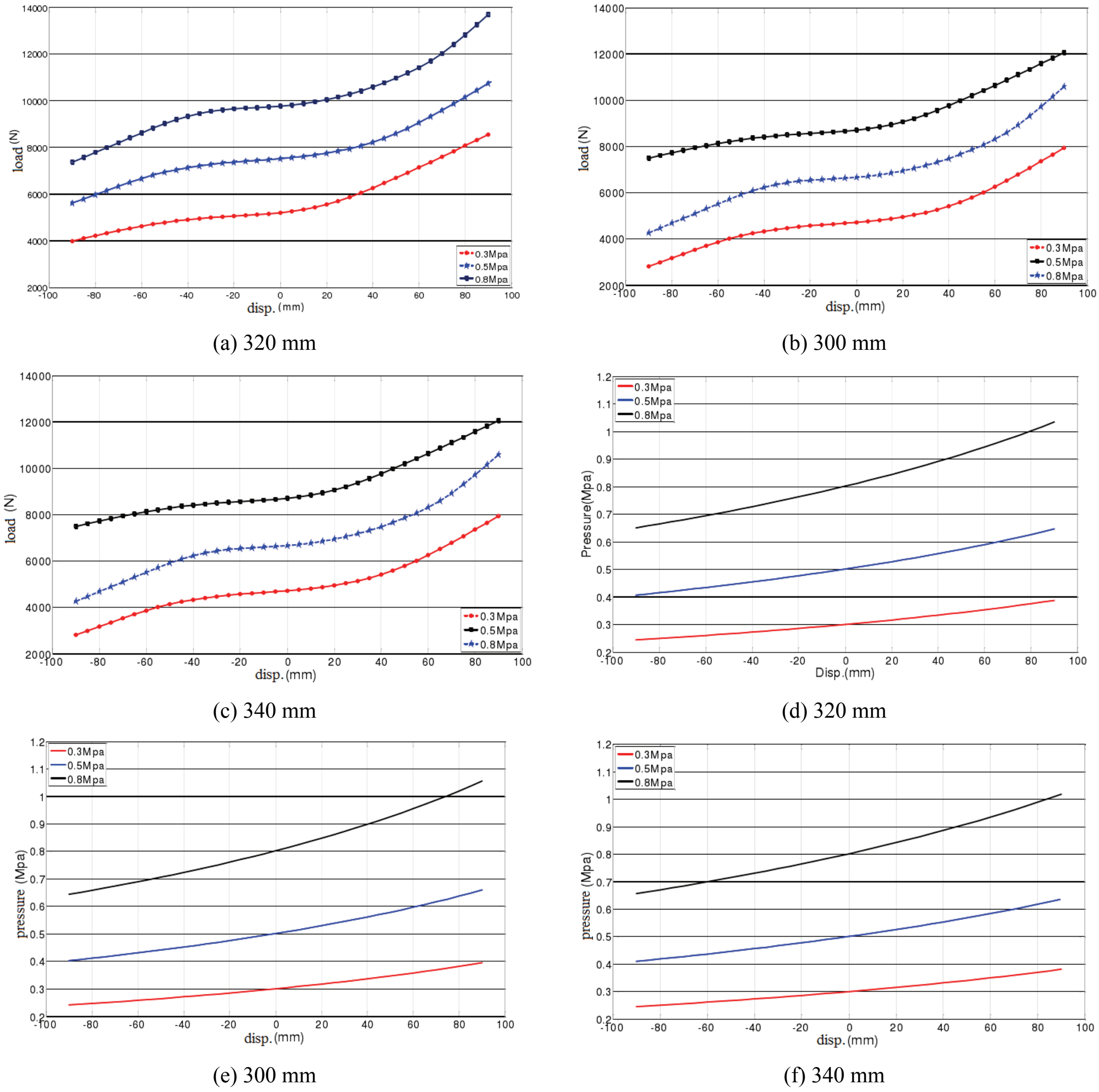
Fig. 2. Principles of MTS vibration test equipment and air springs.

Considering air spring has its own characteristics, the paper uses experimental methods to test air spring so as to discuss the effects of different initial air spring pressure (0.3 MPa, 0.5 MPa, 0.8 MPa) and different initial positions (320 mm, 300 mm, 340 mm) to the air spring. The results are shown in Fig. 3, the former three pictures show that when the initial position is 320 mm, 300 mm, 340 mm, the load and the displacement changes, the latter three pictures show that when the initial position is 320 mm, 300 mm, 340 mm, the pressure and the displacement changes.

2.2. Modeling and Analysis of Air Springs Based on FEM

Using the finite element method (FEM) to model is commonly used analytical tools in the air spring design calculations. It basically need not simplifications, just in accordance with the size of each part of the structure and stiffness characteristics of the material characteristics, these can be simulated ,such as air spring deformation, kinematics of force and displacement, including linear stiffness, nonlinear composite stiffness, gradient stiffness characteristics. Finite element method would also considered contact friction, large deformation and other factors to calculate and analyze, so to accurately simulate the stress and strain of the air spring, the contact status and contact pressure, dynamic stiffness and other characteristics. With different cord angles and different cord distances, the characteristics of the air spring changes.

The following Fig. 4 shows when the initial position is 320 mm, at different air spring pneumatic pressure, the set of curves are there characteristic curves. Under the same pressure, the characteristic curve shapes like anti-"S". The solid line is the simulation results, while the dotted line as the test results. The figure shows that the simulation results are nearly the same as the experimental results, a little deviation just occurs in some locations. The main reason is that in the simulation the model is simplified. Such as during the test, there is a certain temperature change of the air bag which would affect the test results, but in the simulation, it is neglected. It is because of these reasons, there are differences between finite element method results and the experimental test results, but the overall trend is consistent, which indicates that finite element method has certain reference value. So the finite element model can be used to study the parameters of the air spring.



(a) 320 mm (b) 300 mm

(c) 340 mm (d) 320 mm

(e) 300 mm (f) 340 mm

Under different initial pressure, pressure and displacement curve

Fig. 3. MTS vibration test results.

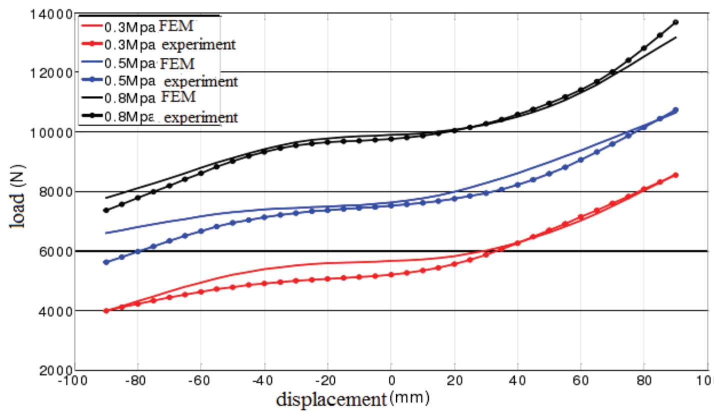


Fig. 4. Comparison of results of FEM and experiment.

3. Air Suspension System Control Algorithm and Hardware in the Loop Simulation

3.1. Air Suspension Control Algorithm

The main role of suspension system is to improve makes the vehicle body and passenger separated from external interference and improve comfort with the car's ability to grip the land. Electronically controlled semi-active / active controlled air suspension has been the rapid developed, high-level air suspension system has begun to adopt active air suspension system (AASS), according to the motion state of the vehicle as well as incentives changes to automatically adjust the air spring stiffness, damping or active damper actuator for controlling parameters such as power, inhibit the body's vibrations and adjust the body posture, reduce body acceleration and tire load, limit excessive dynamic deflection of suspension and body rolling off, so that suspension damping would come to the optimal state and get a good ride comfort and handling stability.

Since the sliding mode control (SMC) algorithm is more suitable for AASS control the paper analyzes on SMC theory, air suspension characteristics and existing research results, to design a fuzzy adaptive sliding mode controller that combines the dynamic characteristics of fuzzy control, so the performance is greatly improved.

Define the state vector as X , control input vector as U , road excitation input vector as W , so

$$X = [x_s, \dot{x}_s, x_u, \dot{x}_u]^T = [x_1, x_2, x_3, x_4]^T$$

$$U = [f] = [u],\ W = [x_r] = [w]$$

The state space equation of the control system can be expressed as:

$$\dot{X} = F(X,t) + G(X,t)U + D(X,t)W$$

$$F(X,t) = \begin{bmatrix} x_2 \\ \frac{1}{m_s}(-cx_2 + cx_4 - f_{ks}) \\ x_4 \\ \frac{1}{m_u}(cx_2 - k_t x_3 - cx_4 + f_{ks}) \end{bmatrix}, \quad G(X,t) = \begin{bmatrix} 0 \\ \frac{1}{m_s} \\ 0 \\ -\frac{1}{m_u} \end{bmatrix},$$

$$D(X,t) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\frac{k_t}{m_u} \end{bmatrix}$$

3.2. Air Suspension Hardware in the Loop Simulation Study

Hardware in-the-loop simulation (HILS), also known as semi-physical simulation, hardware embedded loop simulation, usually puts the mathematical model, entity model and the actual device associated of systems together to form a simulation system. Due to physical intervention to simulation loop, it is real-time simulation, the simulator gets real-time input signal and generates real-time dynamic output, developers can directly see the system control simulation results, and can directly modify the control algorithm based on the simulation results, greatly improving system simulation accuracy. The development method of conventional air suspension control system is a “test - improvement – test” circle, it needs a large number of road tests, while the hardware in the loop simulation technology can greatly shorten the product development cycle, saving a lot of development funds.

dSPACE (Digital Signal Processing And Control Engineering) is a real-time simulation system, developed by a German company named dSPACE, which could seamless connect with MATLAB/Simulink. This paper selects AutoBox series of the dSPACE real-time simulation system. AutoBox processor board is DS1005, with Motorola PowerPC 750 chip as the core processor; SIO Interface Board DS4002 has a multi-channel serial communication interface; input / output board DS2002, DS2101 with multi-way A/D, D/A; CAN bus communication interface board DS4302 CAN is equipped with multi-way channels.

AASS control system developing steps in this article are summarized as follows (Fig. 5).

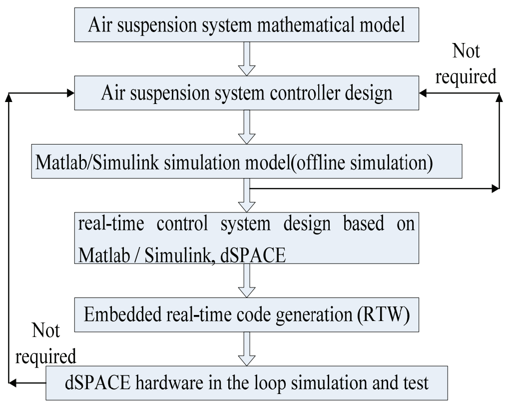


Fig. 5. AASS control system developing process based on dSPACE.

1. Make AASS system dynamics analysis, build AASS mathematical model and analyze its characteristics.
2. According to the AASS system characteristics, analyze the AASS control strategy, select the appropriate control algorithms, design a robust controller of AASS system.
3. Establish Matlab / Simulink model of active control systems and make off-line simulation.
4. Design AASS real-time control system based on dSPACE and Matlab / Simulink.

5. Use real-time simulator provided by RTW and dSPACE tools to generate executable code.
6. Use ControlDesk provided by dSPACE to do real-time simulation and monitoring for active control system.

The test is carried out in strict accordance with the latest car ride test method (GB/T 4970-2009). The test vehicle uses V348 minibuses made by Jiangling Motors Co., Ltd. Data acquisition frequency is 256 Hz. The semi-loop simulation results shows that the conventional sliding mode control and fuzzy adaptive sliding mode control has significantly improved ride performance with active air suspension, fuzzy adaptive sliding mode control has better ride comfort performance and robust stability than conventional sliding mode control.

4. Air Suspension Vehicle Dynamics Modeling and Simulation Test

This paper uses ADAMS and Matlab/Simulink to build model of vehicle air suspension, it establishes vehicle dynamics model of air suspension system of embedded modular, makes simulation and analysis for car under each condition. The main tasks include: establishing bus air suspension dynamics model, including its front suspension, rear suspension, steering system and tires road model; conducting simulation of the bus, including the simulation under different speeds and different road conditions; making the real vehicle ride comfort test and the natural frequency test, to get and ride comfort evaluation and the natural frequency under different roads and different speeds, and verify the correctness of the air suspension simulation model.

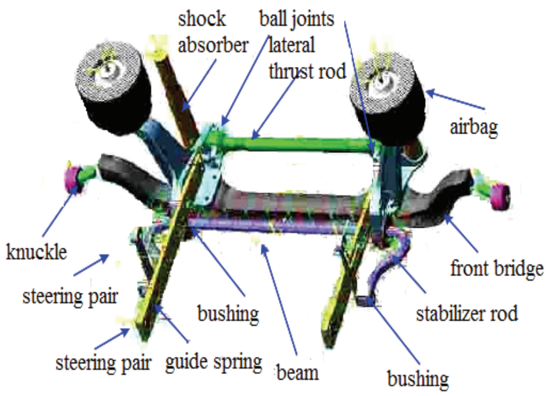
4.1. Vehicle Dynamics Modeling

Air suspension dynamics model includes: front suspension, rear suspension, steering mechanism and tire dynamics model (Fig. 6).

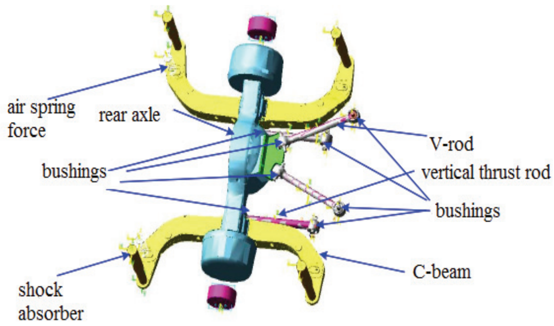
Front suspension dynamics model includes: airbag, guide springs, shock absorbers, lateral thrust rods, stabilizer bar and front axle components. The front suspension has two pieces guide springs, which are located on the left and right of the front axle, transferring longitudinal forces between the axle and the frame.

Airbag is a part transmitting vertical force between the axle and the frame, the front suspension has two airbags on both left and right side. The front suspension includes two shock absorbers, upper end of each shock absorber is connected to frame, and lower end of each shock absorber is connected to the axle.

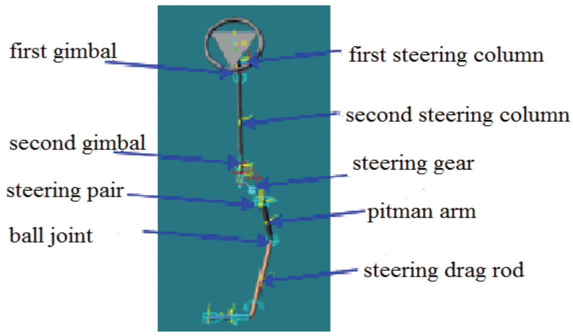
The lateral thrust rod is positioned at a certain place after the front bridge of front suspension, to transfer lateral forces between the frame and axle. Left pivot of lateral thrust rod and frame are connected by ball joint, and right pivot of lateral thrust rod is connected with the right side of the air bag bearings through the ball joint. The stabilizer bar is to prevent a larger car body roll, it is connected to four bushings, wherein the two bushings are connected with front axle, the other two bushings are connected with the left and right brackets of the car frame.



(a) front suspension dynamics model



(b) rear suspension dynamics model



(c) Steering system dynamics model

Fig. 6. Air suspension dynamics model.

Rear suspension bridge structure is a H-type structure, which means that there is a C-shaped beam on each side of the rear bridge, a vertical thrust above each C-beam, two oblique thrusts on the upper part of the rear axle beam rods, and an airbag on each C-beam, a shock absorber outside each air bag.

Steering system is classified as mechanical steering system and power steering system, this paper studies mechanical steering system. Mechanical steering system is made up by the steering mechanism, steering gear and steering linkage component organization. When creating a multi-body model of the steering system steering, it mainly means to build steering operation mechanism model and steering linkage model, and the steering gear is simplified steering as a steering ratio.

For the tire model, currently empirical model proposed by Pacejka and magic formula and other tire models are widely used in the automotive industry. This paper will model follow the magic formula theory.

4.2. Vehicle Road Test for Ride Smoothness of Air Suspension

To assess the ride smoothness of air suspension, it was needed to carry air suspension sample in accordance with national standards GB/T4970 "ride smoothness of car random running test method". 2512 Human Vibration Equipment measured root mean square value and the weighted vibration level Leq of vibration acceleration of the driver's seat, the seat on the left side above the rear axle, the seat on the left side of rear part of the car to evaluate the ride smoothness; with accelerometers to measure vibration acceleration values of front and rear axles corresponding position to analyze air suspension damping characteristics and spectral characteristics.

The test road is classified into two kinds: random road and pulse pavement. When the speed of test bus is 30 km/h, 40 km/h, 50 km/h, 60 km/h on random road and when the speed of test bus is 30 km/h, 40 km/h, 50 km/h, 60 km/h, the acceleration and pulse on each point of air suspension should be measured. Test apparatus includes an acceleration sensor, seat sensor, 32-channel LMS data acquisition and LMS Test. Lab Rev8B processing system, body vibration device, data processing system. Duration of Sampling is about three minutes, the sampling frequency is 1280 Hz, the cutoff frequency is 200 Hz and 500 Hz, the analysis frequency is 500 Hz.

In order to verify the accuracy of vehicle suspension dynamics model, the paper compared simulation data with the experimental data. The comparison is between random road simulation test and pulse road simulation test. Acceleration data of each test point of the vehicle under certain speed could be obtained, through calculating, and root mean square value and weighted acceleration vibration level value Leq could be obtained to evaluate the ride smoothness of the vehicle, shown in Table 2.

Table 2. Comparison of random road and pulse road simulation test.

Speed	Ride smoothness Leq(dB)	Left front seat Leq(dB)		Left seat above rear axle Leq(dB)		Left rear seat Leq(dB)	
40	~	experiment	~	experiment	114.6	experiment	116.3
		simulation	~	simulation	115.1	simulation	116.6
50	≤121.0	experiment	115.0	experiment	116.2	experiment	117.0
		simulation	115.6	simulation	116.5	simulation	116.9
60		experiment	~	experiment	116.8	experiment	118.1
		simulation	~	simulation	117.1	simulation	118.6

From the comparison of experimental data and simulation data, we can conclude that the acceleration power spectral density function and the weighted vibration level Leq through simulation at each seat are relatively close to the experimental results, indicating that the dynamic model of air suspension for random road better in ride smoothness test simulation.

For ride smoothness pulse road test, the paper mainly conducts the experiment with speed of 30 km/h, 40 km/h, 50 km/h and 60 km/h, when simulating the road surface, the paper adds triangle to straight road, the size of triangle is the same as that of actual test.

Compare the maximum value of experimental data for the pulse road test under speed of 30 km/h, 40 km/h, 50 km/h and 60 km/h and simulation data, we could obtain Table 3 to analyze performance of air suspension and judge the accuracy of simulation data, and verify reliability of the model.

Table 3. Comparison of maximum acceleration of experiment and simulation test.

Speed (km/h)			30	40	50	60
Maximum acceleration	Left front seat	Experiment data	9.5	10.2	11.5	11.3
		Simulation data	10.9	10.1	11.3	11.1
	Left middle seat	Experiment data	11.0	11.7	16.3	16.2
		Simulation data	10.1	12.5	16.3	16.6
	Left rear seat	Experiment data	19.9	26.2	25.9	27.9
		Simulation data	20.0	27.1	26.0	24.9

4.3. Natural Frequency Test of Air Suspension System

The experiment methods and simulation methods of natural frequency are in accordance with the national standard GB 4783-84, the test site is standard test site, the venue in ADAMS simulation is a special road model in reference to the standard road model.

After obtaining experiment data and simulation data, the paper uses the time history method to analyze natural frequency. With 20 Hz low pass filter to filter the time histories of acceleration data obtained by experiment and simulation, with the help of MATLAB, the paper obtains the curve shown in Fig. 7 and Fig. 8, wherein the red solid line is for the experimental data, blue dotted line is for the simulation data.

The natural frequency obtained by simulation:

$$f = \frac{1}{T} = \frac{1}{3174-2348} = \frac{1}{826} = 1.21Hz$$

The natural frequency obtained by experiment:

$$f = \frac{1}{T} = \frac{1}{3156-2375} = \frac{1}{781} = 1.28Hz$$

The deviation of natural frequency obtained by simulation and natural frequency obtained by experiment is small, so the dynamic model of air spring can be used for air suspension to simulate the natural frequency of the car.

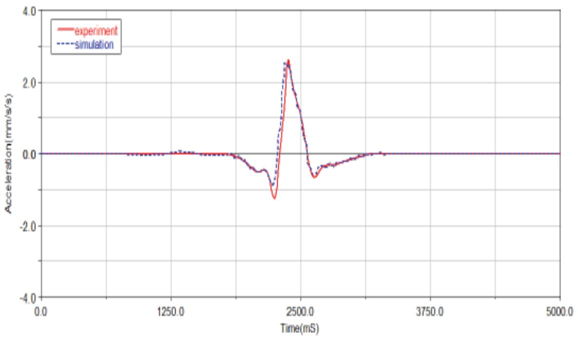


Fig. 7. Acceleration curve of the left side airbag after filtering.

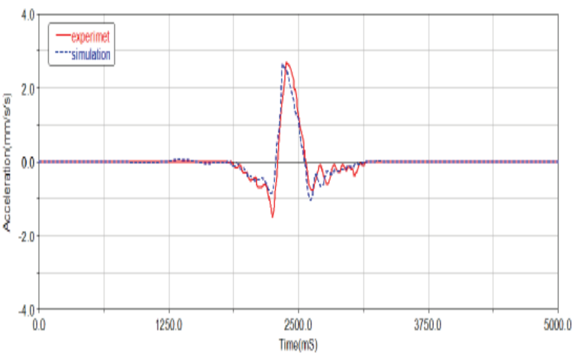


Fig. 8. Acceleration curve of the right side airbag after filtering.

5. Conclusion

Establishing a unified air suspension system dynamics model and control system development platform has important application value for improving the overall performance of the air suspension system. The research idea is theoretical analysis – experimental study – dynamics modeling and simulation analysis. The paper finishes the following tasks: using numerical analysis method to establish the dynamic model of the air spring system; establishing a material nonlinear and contacts nonlinear finite element dynamics model of the air spring; Introducing fuzzy adaptive control sliding mode control algorithm, using hardware in the loop simulation technology to design active air suspension controller; using multi-body dynamics and finite element modal analysis technique to establish air suspension multi-body vehicle dynamics model, and making road testing and simulation evaluation according to the national standards.

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