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TEST AND SIMULATION OF THE ELECTRONIC CONTROL SUSPENSION SYSTEM OF SEMI-TRAILER BASED ON SIMULINK

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ABSTRACT

Aiming at the poor matching of the existing semi-trailer air suspension system, such as vehicle roll, airbag leakage and airbag response time after single airbag failure, the semi-trailer electronic control air suspension system is designed. The three-dimensional model and simulation model of semi-trailer electronic suspension system are established by using Creo and Simulink simulation software. The existing air suspension electronic control logic (ECAS), system layout and configuration are optimized to improve the turning stability, airbag response speed, static air tightness and NVH of semi-trailer air suspension. Through Simulink and ADAMS/car simulation analysis and vehicle carrying test, the simulation results and test data are analyzed, and finally the closed-loop control logic with supercharger is determined to adapt the novel control logic and system layout. The simulation and test results show that when the air compressor opening time is 3.5 s, the solenoid valve frequency is 22 kHz and the air pressure difference is 5.6 bar, the system response is the fastest and the energy consumption is the lowest.

KEYWORDS: semi-trailer; ECAS; air suspension; NVH.

INTRODUCTION

With the rapid development of China's economy, the demand for semi-trailers has also increased, and the total sales of semi-trailers in 2020 will exceed 5 million units (Chen, 2018). With the increase in the amount of semi-trailers, there are more and more problems exposed by semi-trailers, mainly vehicle overloading and vehicle accidents caused by overloading. To this end, the country has promulgated laws and regulations such as GB7258 to avoid vehicle overloading from the source of vehicle production., the most important method is to install the vehicle air suspension system (Shi, 2021; Cao, 2021). Air suspension can effectively prevent vehicle overloading, and at the same time,

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air suspension can effectively reduce vehicle damage to the road surface, improve driving comfort and handling stability (Wang, 2021).

At the beginning of the 20th century, the first patent for automotive air suspension was officially granted, and a car equipped with air suspension came out four years later (Xu, 2021). In the 1950s, due to the emergence of synthetic rubber, the commercialization and engineering application of air suspension gradually gained popularity (Kou, 2019; Martyanov, 2021). After more than a century of development, air suspension has also experienced various changes such as "leaf spring airbag composite suspension - passive full air suspension - active full air suspension (electronically controlled air suspension system)". The existing semi-trailer air suspension system has great drawbacks and poor systematic matching, such as vehicle roll, airbag leakage, and airbag response time after a single airbag fails (Zhang, 2021； Zhou 2020).

In view of the urgency of equipping semi-trailer with air suspension and the applicability of air suspension, this paper realizes the optimization and improvement of the semi-trailer air suspension system from the aspects of vehicle selection, test analysis, optimization and improvement, simulation and re-test, etc. And the feasibility of the optimized scheme is verified by simulink simulation software.

1 Design principle and structure

1.1 Overall structure

Replace the traditional leaf spring of the Semi-trailer with an air spring, and adjust the height of the spring and the supporting force of the spring by controlling the air pressure in the air spring. The overall arrangement is shown in Fig. 1.

1.2 Working principle

The closed-loop compressor-type air suspension system uses the engine air compressor to inflate the air reservoir. When the air reservoir pressure reaches the specified value, the airbag is inflated and deflated by the closed-loop self-contained compressor, so as to realize the adjustment of the body height.

When working, the height sensor collects the body height signal. After the processor receives the signal, the body height can be adjusted by changing the airbag pressure.

The closed-loop system with its own air compressor can realize two-way air compression, which can achieve the purpose of zero air emission, energy saving and environmental protection.

2 Key components and control methods

2.1 Key Components

The air suspension system is an adjustable air spring system that replaces the traditional leaf spring or spring. It consists of an air supply system, a control system, a signal acquisition system and an execution system.

The air supply system generally has three methods: auxiliary air intake, APU air intake or independent air storage cylinder. The air supply unit needs to be equipped with a one-way valve to ensure that the air suspension system can continue to work when other circuits fail. to ensure the normal running of the vehicle.

The signal acquisition system is composed of pressure sensor, altitude sensor, temperature sensor and gyroscope. The height valve collects the body height information in real time, the air pressure sensor collects the air bag pressure, the air tank pressure and the compressor pressure, the temperature sensor monitors the air compressor temperature and the ambient temperature, and the gyroscope monitors the body posture.

The control system is compiled with ARM single-chip microcomputer and Linux system. The control system includes 8-channel PWM controller, 6-channel AD conversion module and CAN communication module. The basic principle is that the signal processing system collects sensor signals, and then outputs PWM signals and voltage signals to control the ECAS valve and air compressor after analyzing the behavior of the single-chip microcomputer. The control system can calculate the cargo weight of the vehicle through the collected airbag pressure and the body. When the cargo weight exceeds the allowable load, the control system will first issue an alarm. If the vehicle is forced to drive, the control system will release the airbag pressure, so that the vehicle will drop to At least the spring support is lost, so that the vehicle cannot be driven, so as to prevent the vehicle from being overloaded.

The execution system includes an air compressor, an ECAS valve and an air spring. During operation, the ECAS valve controls the gas pressure in the air spring to change the body height.

2.2 Control system design

The principle of the optimized Semi-trailer air suspension control system is shown in Fig. 2, including automatic control and manual control.

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2.3 Control system hardware

The hardware of the Semi-trailer air suspension control system is mainly composed of embedded micro-controller (MCU), Semi-trailer information communication equipment (CAN Protocol), information acquisition sensor group, PWM drive module and motor drive module.

The micro-controller adopts STC12C5A60S2 single chip microcomputer, which is 8-12 times faster than the traditional 8051 single chip microcomputer. The working voltage is 3.5-5.5 V. Besides, Max810 special reset circuit is integrated in the single chip microcomputer to support ISP and PWM. It is equipped with 2-way UART and 8-way high-speed 10 bit A/D conversion (250K/s). It also has the functions of overheating shutdown latch, over-voltage protection lock and under-voltage shutdown, and adds watchdog and PWM module. Selecting the embedded Micro-controller as the control core can not only ensure fast and accurate operation, but also control the motor in strong interference situations, and its pin resources are rich, which is conducive to peripheral control and data reading.

2.4 Control strategy

The control strategy adopts closed-loop control logic of closed-band supercharger. The specific control strategy is shown in Fig. 3.

Closed loop control is that the compressed air is uniformly recycled through the booster during the control process and will not be discharged into the atmosphere, so as to achieve the purpose of energy saving, consumption reduction and response improvement. Meanwhile, using the existing Semi-trailer control mode for reference to increase the directional valve can effectively improve the control accuracy and response speed.

The Semi-trailer is divided into three height levels L1, L2 and L3, and the relative height of the frame is 100, 150 and 200mm respectively. When working, first judge the Semi-trailer speed, because when the Semi-trailer speed is low, the Semi-trailer may be passing through the undulating road. At this time, it is necessary to increase the ground clearance of the Semi-trailer to ensure the trafficability of the Semi-trailer. Besides, when driving at low speed, the wind resistance and emergency braking have little impact, so the minimum mode will not be started. When the Semi-trailer speed is greater than 30Km/h, the Semi-trailer height will be adjusted to L2 in order to reduce the Semi-trailer wind resistance and improve the Semi-trailer handling. At this time, the balance between fuel economy and handling is the highest. When the speed is greater than 30Km/h, the Semi-trailer turns sharply, and the Semi-trailer is prone to rollover and rollover. In order to prevent the Semi-trailer from rolling

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and rollover, when the sensor collects the Semi-trailer emergency forwarding signal (judged by Semi-trailer speed, steering angle and gyroscope), the Semi-trailer will quickly connect the left and right air springs through ECAS valve and steering valve. At the same time, the height of the left and right air springs will be adjusted through the supercharger to ensure the body attitude. When the Semi-trailer turns sharply to the left, the controller will quickly transfer the gas in the left air spring to the right air spring through the booster according to the Semi-trailer angle and speed to stabilize the body attitude. When the Semi-trailer turns sharply to the right, the controller will quickly transfer the gas in the right air spring to the left air bag through the booster according to the Semi-trailer angle and speed. In the process of gas transfer, the body height sensor will monitor the side height and Semi-trailer direction angle in real time, and adjust the height of left and right air springs in real time.

When the Semi-trailer speed is greater than 30Km/h and braking is conducted, the controller will reduce the height of the air spring according to the Semi-trailer speed and pedal stroke, so as to reduce the forward inclination angle of the Semi-trailer and improve the stability of the Semi-trailer during braking.

When the controller monitors the Semi-trailer braking and the speed is greater than 30Km/h, the controller opens the ECAS valve and steering valve to connect the air spring and low-pressure air reservoir, and quickly compresses the gas in the air spring into the low-pressure air reservoir through the booster. In this process, the compressed gas will not be discharged into the atmosphere to form a closed-loop control, which can reduce Semi-trailer energy consumption and achieve the purpose of energy conservation and emission reduction.

3 RESULTS AND DISCUSSION

3.1 Establish a mathematical model

In order to establish a model for filling and deflating the gas cylinder, and to simulate the pressure boosting process of the gas cylinder when the gas cylinder is replenished or the air spring is lowered, the mathematical model in the gas cylinder is established according to the dynamic characteristics of the gas in the gas cylinder, the gas state equation and the first law of thermodynamics:

$$q_{mt} = \frac{V_t}{RT_t}\left(\frac{dp_t}{dt} - \frac{p_t}{T_t}\frac{dT_t}{dt}\right) \qquad (3\text{-}1)$$

q_{mt} -The mass flow rate in and out of the gas tank； T_t—the gas temperature of the gas tank；

R is the gas constant; V_t is the volume of the gas tank; Pt is the absolute pressure of the gas tank.

The air spring model is established by referring to the mathematical model of the air storage tank as

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follows

$$q_{ms} = \frac{V_s}{RT_s}\left(\frac{dp_s}{dt} - \frac{p_s}{T_s}\frac{dT_s}{dt} + \frac{p_s}{V_s}\frac{dV_s}{dt}\right) \quad (3\text{-}2)$$

q_{ms} is the mass flow rate in and out of the air spring; Ts is the gas temperature in the air spring; R is the gas constant; Vs is the volume of the air spring;
Ps is the absolute pressure of the air spring.

In order to facilitate the establishment of the model, the ECAS valve is simplified as a constricted orifice. The passage of the ECAS valve is 3mm and the length is 12mm. Therefore, the ECAS valve model is simplified as a thin tube with an inner diameter of 3mm and a length of 12mm. According to the molar mass formula and Bernoulli's formula, we can get

$$\mathrm{p} + (1/2) * \rho \mathrm{v}^2 = \mathrm{C} \quad (3\text{-}3)$$

p is the relative pressure difference (the pressure difference between the two ends of the ECAS valve) ;
ρ is the gas density ; v is the speed of the gas flowing through the valve body ; C is a constant。

Only the air compressor and solenoid valve generate energy consumption in the whole system. The energy consumption of the solenoid valve is relatively low. To simplify the simulation, the energy consumption of the solenoid valve is ignored, and only the energy consumption of the air compressor is calculated. The energy consumption of the air compressor is mainly related to the air pressure difference and flow rate, so the energy consumption of the air compressor can be calculated according to the air pressure and volume changes of the air spring and the air storage cylinder.

$$W_c = \int_0^t \omega_c q_c dt \quad (3\text{-}4)$$

Among them W_c is the energy consumption per unit mass of the air compressor, ω_c is the mass flow rate of the air compressor.

The calculation of energy consumption is based on the law of conservation of energy, the ratio of the potential energy change caused by the change of the vehicle height to the energy consumption of the air compressor and the energy pressure change of the air tank. The specific working parameters are shown in Table 1.

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3.2 Simulation

Creo, Simulation and ADAMS/CAR simulation software are used to establish an 8x4 truck air suspension model. The simplified digital model of the air suspension system is shown in Figure 4. The model is reversely mapped through the rear axle suspension system of the 8x4 truck. Rear axle suspension model, the model includes axle, wheel, leaf spring and air spring.

The vertical support force and relative height of the air spring are calculated by ADAMS/CAR simulation software, and a 1/4 suspension system model is established. Then the vertical support force and height of the air suspension system are simulated by the simulation software. And the vehicle body stability simulation is conducted, as shown in Figure 5.

The pressure in the air spring changes with the height of the vehicle body. Therefore, a mathematical model is used to simulate and analyze the pressure in the air spring. The height of the vehicle body will increase rapidly with the increase of the pressure of the air spring. The body height decreases rapidly as the air spring pressure decreases.

In order to verify the feasibility, response speed, balance and energy consumption of the control logic, the control logic is added to the mathematical model, and then the control logic is optimized through simulation. The simulation results are shown in the solid line in Figure 6, which simulates the influence of different air pressure differences between the air storage tank and the air bag and the opening time of the air compressor on the body response. At the same time, in order to verify the accuracy of the simulation, the same parameters of the simulation are set on the test vehicle for analysis, and the results are shown in the dotted line in Figure 6.

From the simulation and test results, the simulation results are similar to the actual test results, and the deviation is within 3%. In addition, the four curves in the figure are the airbag pressure change curves under different air pressure differences. The longer the air compressor starts, the higher the energy consumption. The smaller the air pressure difference, the shorter the inflation time but the longer the deflation time, and the valve body opens. The higher the frequency is, the higher the response is. Therefore, after the simulation, the optimal result is that when the air compressor is turned on for 3.5 s, the solenoid valve frequency is 22 kHz, and the air pressure difference is 5.6 bar, the system has the fastest response and the lowest energy consumption.

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3.3 Test verification

In order to determine the specific working parameters: valve body opening time and air compressor operation time transfer parameters, relevant tests are conducted on the vehicle. It mainly measures vehicle air suspension pressure, ECAS valve inlet and outlet pressure, air storage tank pressure and air compressor inlet and outlet pressure.

The test equipment mainly includes data recorder (Stidford PPC PAD), 16-way barometric pressure sensor, temperature sensor, and 4-way displacement sensor (as shown in Figure 7).

To verify the response speed of the vehicle attitude and air suspension under different speeds, different rotation angles and emergency braking conditions, the switching response test of the system under different modes is shown in Figure 8. The test results of the traditional control method mainly include the air pressure difference responding speed.

According to the simulation and test results, the following orthogonal test is designed, and it can be verified that the system can keep the vehicle body posture stable under different inclined road conditions. The single-factor experiment is used to carry out the orthogonal combination design test. The test factors and coding levels are shown in Table 2. Then the vehicle attitude (front, rear, left and right inclination angles) was measured under the orthogonal test, see Table 3.

Due to the air pressure difference between the high and low pressure air storage tanks in the test, different parameters are set for the running time of the air compressor to meet the vehicle response requirements. At the same time, in order to ensure the front and rear inclination angles and the left and right inclination angles of the vehicle, the valve body opening evaluation rate is controlled to meet the response of the vehicle closed-loop control. As shown in the test results, in A3B2C4, the results meet the requirements and the effect is the most worrying, so the opening frequency of the valve body is selected as 20kHz and the air compressor time is 4s. Therefore, the control system and arrangement can improve the measurement response speed and reduce the energy consumption under the moving frequency and the opening time.

4 CONCLUSIONS

1) When the solenoid valve opening frequency is 20kHz, the temperature and response speed of the solenoid valve satisfy the closed-loop control system.

2) The simulation and test results show that when the air compressor opening time is 3.5s, the solenoid valve frequency is 22khz and the air pressure difference is 5.6bar, the system response is the fastest and the energy consumption is the lowest.

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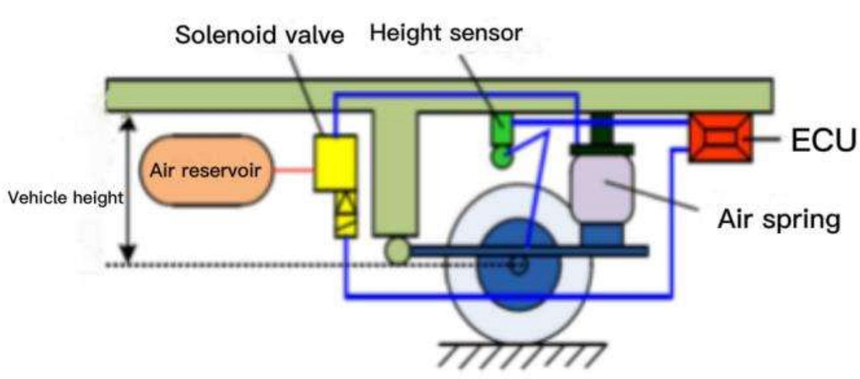

Fig. 1 Schematic diagram of ECAS system overall structure

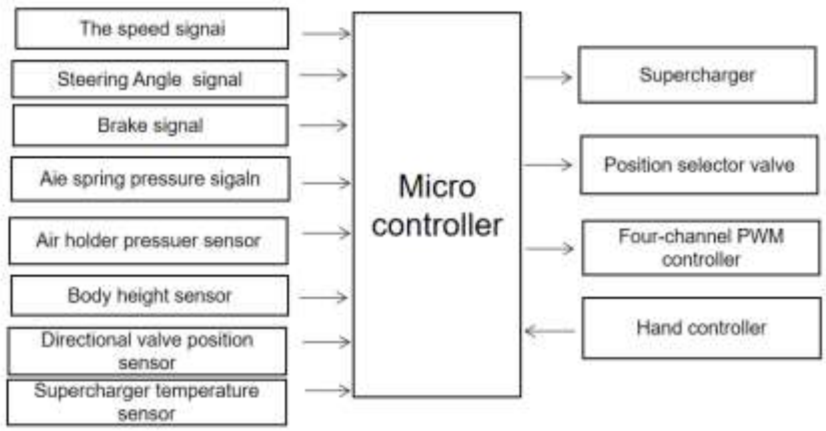

Fig. 2 – Schematic diagram of control system

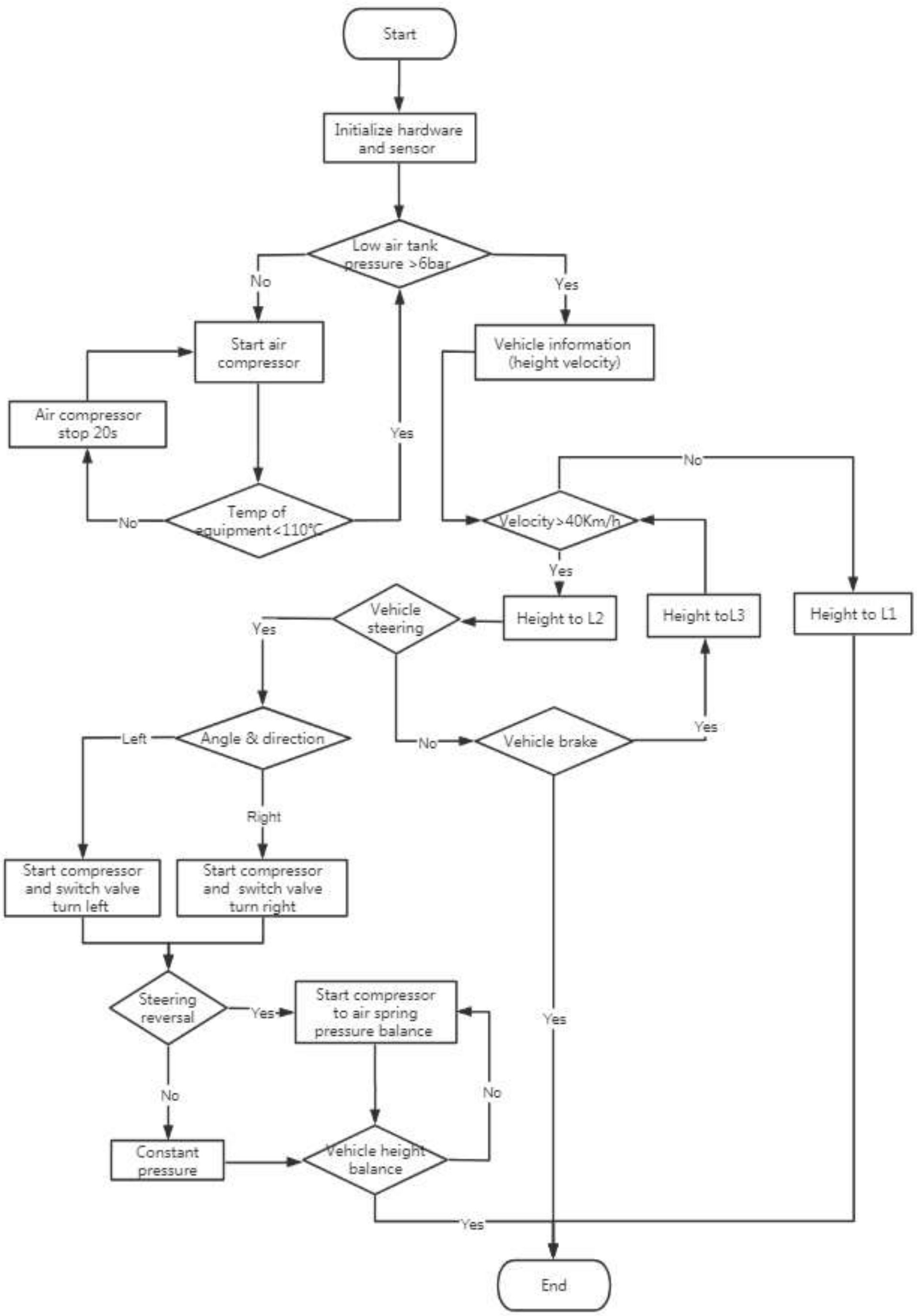

Fig. 3 – Closed loop control flow chart

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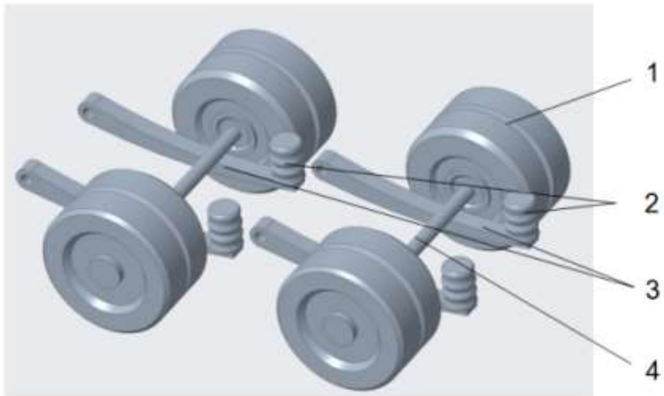

1. Middle rear axle wheel 2. Middle rear axle air bag 3. Middle rear axle leaf spring 4. Middle rear axle axle

Fig.4 Air suspension model

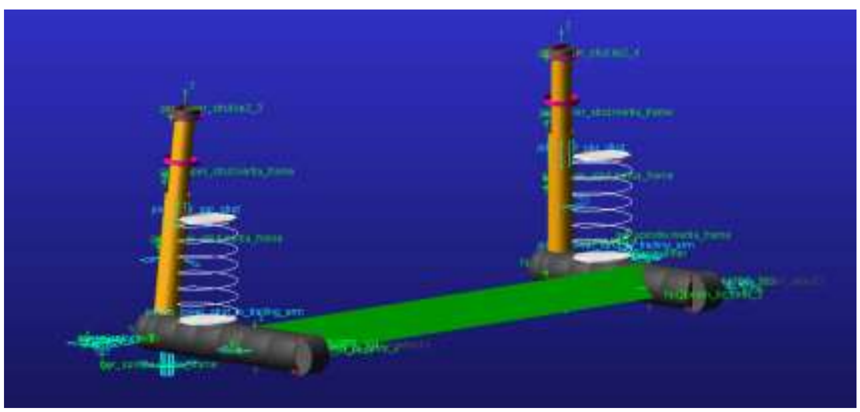

Fig.5 Air suspension model

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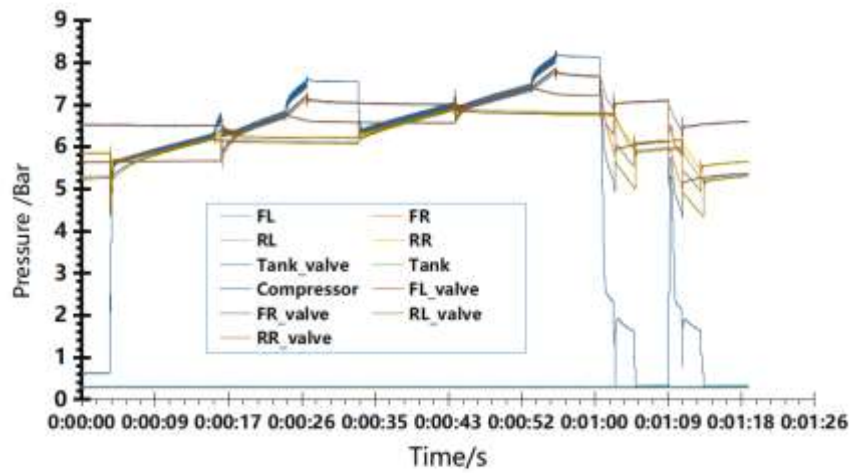

Fig.6 Simulation and test results

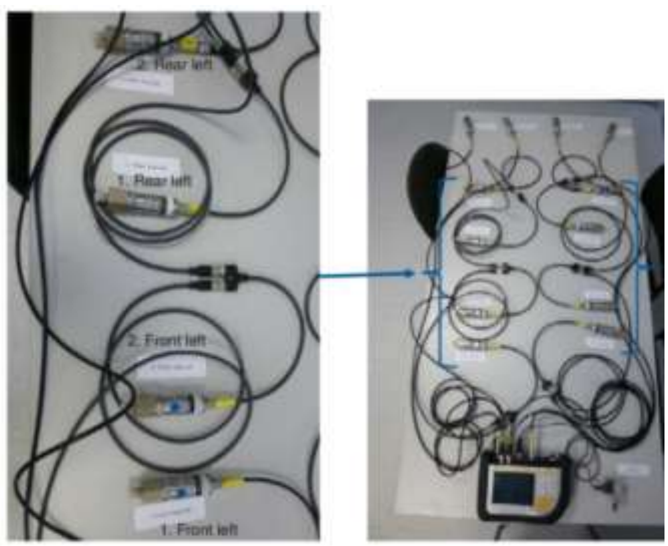

Fig.7 Test equipment

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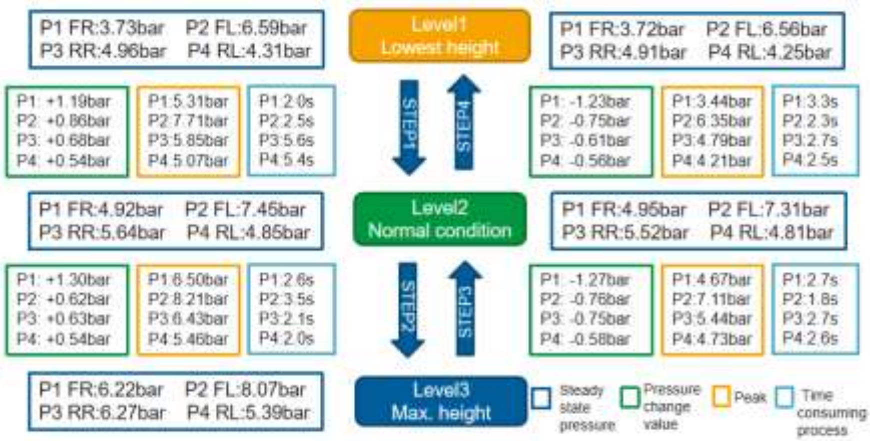

Fig.8 Test results

Table 1 Working parameters

Project	Parameter
Air reservoir volume V_t（L）	35
Air spring load M (kg)	1.5t
Air spring effective area S_S（m^2）	0.012
Connecting Pipe Specifications（mm）	8*1
Connecting line length L（mm）	1200
Body height h（mm）	0-300

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Table 2 Factors and levels

Level \ Factor	Valve body opening frequency f1 （Hz）	Air compressor on time t2（s）	Air tank pressure P（bar）
1	5000	3	4
2	15000	4	5
3	20000	5	6
4	25000	6	7

Table 3 Experimental results analysis

Test no.	Front and rear inclination /%	left and right inclination/%	Response time/s
A1B1C1	-0.9	0	7
A1B2C2	0.6	0.5	6.5
A1B3C3	1.5	1	7.1
A1B4C4	-0.8	0	8
A2B1C2	0.4	0.7	5.2
A2B2C1	0.3	-0.2	3.5
A2B3C4	0.2	-0.1	3
A2B4C3	-0.1	0.1	4.2
A3B1C3	0.3	0.2	3.5
A3B2C4	-0.9	0	6.1
A3B3C1	0.6	0.5	5.1
A3B4C2	1.5	1	6

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A4B1C4	-0.8	0	5
A4B2C3	0.3	0.2	4.5
A4B3C2	-0.9	0	3.5
A4B4C1	0.2	0.1	5.7