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Dynamic Modeling and Experimental Verification of Bus Pneumatic Brake System

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Abstract: The dynamic characteristic of pneumatic brake system is very important, so the full-parameter model of the pneumatic brake system was established on the base of the technology of computer simulation. Its key brake components include brake valve, relay valve, diaphragm brake chamber and pneumatic circuit. AMESim was first introduced on the basis of mathematical derivation. So the multivariable complexity derivation, nonlinear mathematical relationship can be avoided. The model can be used for the bus brake system multi-parameter simulation and design. A pneumatic brake system test-bed was designed to verify the accuracy of the model. It can measure the dynamic characteristic and the output response coordination of each component. It was showed that the simulation results were fit to the experiment results. For the deviation, the explanation and analysis were also given. The response hysteresis of the brake system is mainly caused by the rubber diaphragm deformation in brake chamber. This research laid the foundation for the further structural optimization of brake components and fitness analysis of the pneumatic brake system.

Keywords: AMESim, dynamic characteristic, modeling, pneumatic brake system.

1. INTRODUCTION

Pneumatic brake system has the advantages of simple structure, large braking force, none recycling of working medium. At the same time braking process of pneumatic brake system is a complicated multi-variable, nonlinear and strong coupling process. From braking requirements, the brake response of instantaneous pressure needs to be taken into account. If only considering the static characteristics, the analysis results and the actual situation will have a larger gap. China national standard GB12676-1999 *the structure, performance and test methods of automotive brake system* [1] and GB7258-2012 *Motor vehicle safety technical conditions* [2] are Chinese motor vehicle safety specifications. Strict requirements are proposed for automotive brake system. So the study on dynamic response characteristics for braking systems is necessary. Domestic and foreign scholars have done a lot of researches on the establishment of pneumatic brake system model. The bond graph model was established by Chen Yan *et al*. [3] of Ludong University which includes dual-chamber brake valve, pneumatic circuit, chamber, emergence relay valve and gas flow in pipe. The model shows the dynamic simulation process of the brake system. *et al*. Li He [4] from Huazhong University of Science and Technology modeled and simulated the key components and the whole pneumatic brake system with MWorks. The relationship between pedal force and pressure in the chamber, and the dynamic response of systems were analyzed. Texas A&M University [5] in USA modeled the pneumatic subsystem of a drum air brake system and proved the dynamic response of the model is good. In order to improve the accuracy of pneumatic brake systems for large vehicle braking, Fanping Bu *et al*. [6] established non-linear model and robust design of the pneumatic brake system, put forward the corresponding control strategy, improved the stability of the whole pneumatic brake system. To sum up, the dynamic modeling has some problems that the model is incomplete and the mathematical derivation is too complex. In order to improve modeling accuracy, mathematical model by the theoretical analysis is unable to meet the current demand for automobile research and development. It is necessary to use the perspective of physical models accurately to analyze the brake system pressure delay. Therefore multidisciplinary modeling software AMESim is introduced to complete the internal key components of pneumatic brake system modeling. It can use graphic modeling method based on physical model to avoid complex mathematical relationships derivation.

2. PRINCIPLES AND REQUIREMENTS OF PNEUMATIC BRAKING SYSTEM

In pneumatic brake system dual-circuit brake is commonly be used. When braking, the different braking pressure can be obtained by the key brake components such as brake valve and relay valve [7]. The performance of the key control elements directly affects the dynamic response characteristics of the pneumatic brake system. The dynamic characteristic of the braking system includes brake response time and brake rescission time. The brake response time is from the pneumatic brake valve feeling pedal force to brake chamber outputting required work pressure; Brake rescission time is from the pedal force disappearing to the compressed air in brake chamber excluding out. China national standard GB12676-1999 provides brake response time must not exceed 0.6 s, brake rescission time must not exceed 0.8s. Therefore, in order to ensure braking response output, brake valves, relay valves and brake chamber must be in good coordination of rapid response and output, ensure that the high pressure air transfers to brake chamber rapidly.

3. MODELING OF PNEUMATIC BRAKE SYSTEMS

3.1. Brake Valve Modeling

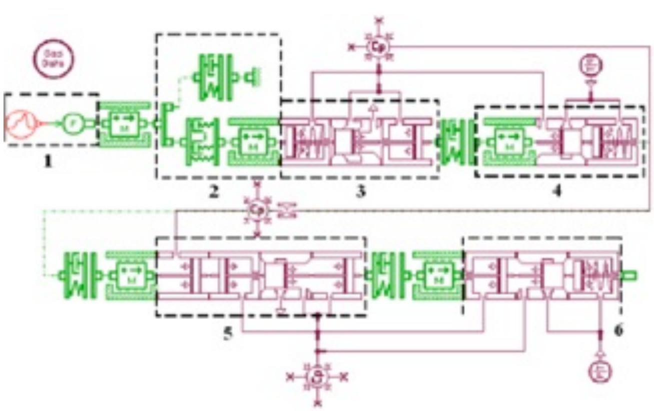
Pneumatic brake valve is the main control device of pneumatic driving system. It is to control the amount of compressed air from air tank to each brake chambers, implement sensitive follower control in the process of brake response and brake rescission. In the braking process, the control equation of the piston in upper and lower cavity of brake valve can be written as (1) and (2).

$$F_{\mathrm{t}} + P_{21}A_{\mathrm{su}} = P_{21}A_{\mathrm{pd}} + P_{11}A_{\mathrm{sd}} + k_2x_2 + F_{\mathrm{ps}}$$
$$+[k_0(x_0 - x_1) + k_1x_1] + F_{\mathrm{ss}} \quad (1)$$

$$F_{\mathrm{t}}' + P_{22}A_{\mathrm{su}}' + P_{21}A_{\mathrm{pu}}' = P_{22}A_{\mathrm{pd}}' + k_2'x_2'$$
$$+P_{12}A_{\mathrm{sd}}' + F_{\mathrm{ss}}' + P_{12}A_{\mathrm{sd}}' + F_{\mathrm{ss}}' \quad (2)$$

where P_{11} and P_{12} are the inlet pressure of upper and lower cavity of brake valve (kPa); P_{21} and P_{22} are outlet pressure (kPa); F_t is pedal force (N); k_0, k_1 and k'_2 are spring elastic stiffness (N/mm); F_{SS}, F_{ps} and F'_{ss} are spring pre-pressure (N); A_{sd}, A_{su}, A_{pd}, A'_{su}, A'_{pd} and A'_{sd} are bearing area of the pistons and valves (mm^2).

According to the physical structure and working principle of series dual-chamber brake valves, a brake valve has valve body, control subjects (push rod, balance spring, small piston, valve assembly, big piston and reset spring) and exhaust valve seats, etc. Brake valve completes the pressurization, dwell, reducing pressure control processes with the interaction between mechanical and pneumatic. The model built in AMESim is shown in Fig. (**1**). The values of brake valve model parameters are shown in Table **1**.



1-pedal signals; 2-rubber balance springs; 3-piston assembly in upper cavity;4-intake valve assembly in upper cavity;5-big piston in lower cavity;6- valve assembly in lower cavity

Fig. (1). Series dual-chamber brake valve model.

Table 1. Values of brake valve model parameters.

Parameter	Unit	Numerical Value
Rubber balance spring stiffness	N· mm^{-1}	Data*
Upper cavity piston diameter	mm	56.45
Push rod diameter of piston	mm	22.80
Piston return spring stiffness	N· mm^{-1}	1.63
Spring pre-pressure	N	48.20
Lower cavity piston diameter	mm	69.62
Push rod diameter of piston	mm	19.64
Valve outer diameter	mm	31.00
Valve inner diameter	mm	25.00
Valve hole diameter	mm	20.00
Valve spring elasticity coefficient	N· mm^{-1}	3.29
Valve core return spring pre-pressure	N	55.93

*Rubber balance spring stiffness is not a specific value, but a variable.

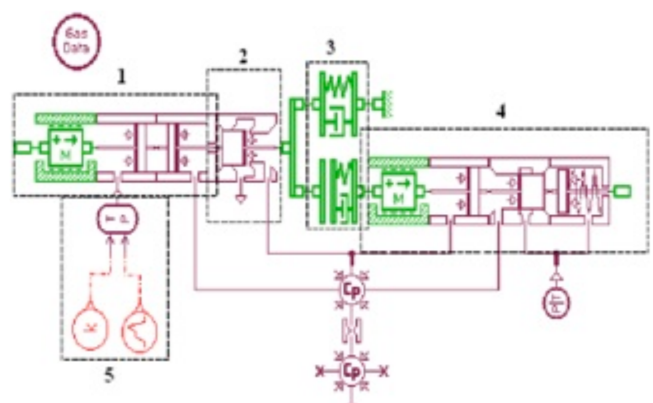
3.2. Relay Valve Modeling

The relay valve is used to let the compressed air in pneumatic brake circuits directly filling into the brake chamber without through the brake valve. So it can shorten the inflation time and accelerate the brake. Relay valve is composed of brake cavity and control cavity. When braking, the control piston moves down to open the inlet valve. The equilibrium equation is shown in (3).

$$P_0A_{Pu} = P_1A_{\mathrm{sd}} + P_2A_{Pd} + k_1x_1 + F_{\mathrm{ss}} \quad (3)$$

where P_0 is control hole pressure (kPa); P_1 is inlet pressure (kPa); P_2 is outlet pressure (kPa); A_{sd} and A_{Pd} are bearing area of the pistons and valves (mm^2); k_1 is reset spring stiffness (N/mm); F_{ss} is spring pre-pressure (N).

According to the physical structure and working principle of relay valve, control element is consists of piston, valve assembly, reset spring. It has three ports (control port A, outlet port B, air supply port C) and exhaust valve. The relay valve model built in AMESim is shown in Fig. (**2**). The values of relay valve model parameters are shown in Table **2**.



1-relay valve control port A; 2-exhaust valve; 3- valve core elastic contact area; 4-inlet valve assembly; 5-pressure signal.

Fig. (2). Relay valve model.

Table 2. Values of relay valve model parameters.

Parameter	Unit	Numerical Value
Control piston diameter	mm	84.36
Piston reduced pressure rod diameter	mm	21.00
Outlet valve hole inner diameter	mm	15.23
Outlet valve hole outer diameter	mm	25.70
Inlet valve hole outer diameter	mm	33.40
Inlet valve hole inner diameter	mm	23.90
Spring pre-pressure	N	21.32
Spring elasticity coefficient	N· mm^{-1}	1.32

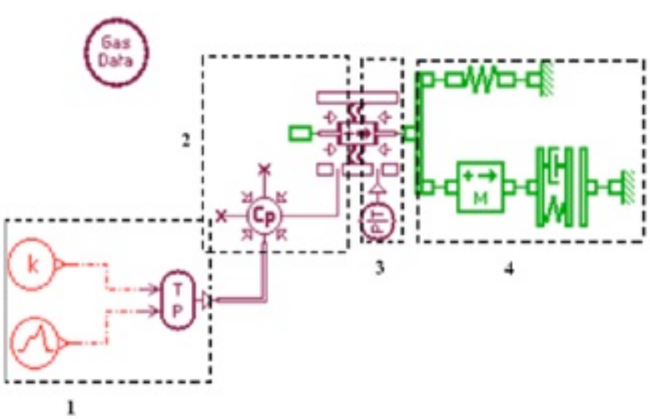
3.3. Brake Chamber Modeling

Brake chamber converts pressure of compressed air into mechanical thrust, acts on braking adjusting arm to brake the wheel. The control equations are shown in (4).

$$\begin{cases} V\dfrac{dP}{dt} = -P\dfrac{dV}{dt} + mR\dfrac{dT}{dt} + RT\dot{m} \\ C_v m\dfrac{dT}{dt} = \alpha A(T_0 - T) + RT\dot{m} \end{cases} \quad (4)$$

where V is brake chamber volume (mm^3); R is ideal gas constant (J/kg·K);C_v is Specific heat at constant volume; α is Heat transfer coefficient; A *i*s cooling area (mm^2); $\dot{m}$ is mass flow rate (kg/s); m *is* air mass which enter the brake chamber (kg); T_0 is standard ambient temperature (K); T is the current environment temperature.

Diaphragm brake chamber model is established by AMESim shown in Fig. (**3**). The values of diaphragm brake chamber model parameters are shown in Table **3**. It is used for simulation of brake chamber's dynamic characteristics (P-t curve) and input-output curve (F-p curve) when brake system is working.



1- air pressure signal; 2- rubber plate;3- piston plate; 4- brake push rod

Fig. (3). Diaphragm brake chamber AMESim model.

Table 3. Values of diaphragm brake chamber model parameters.

Parameter	Unit	Numerical Value
Anterior chamber diaphragm diameter	mm	126-185
Posterior chamber diaphragm diameter	mm	150-207
Piston diameter	mm	86
Push rod diameter	mm	24
Reset spring elasticity coefficient	N· mm^{-1}	k1=0.14x+0.29*
Reset spring's largest amount of compression	mm	25

*Reset spring elasticity coefficient k1 is the function of x (x stands for the displacement of reset spring away from equilibrium position).

3.4. Whole Brake System Modeling

Pneumatic brake system is composed of key brake components and basic pneumatic circuit. The above key brake components full-parameter models can be connected by pneumatic circuit. The complete pneumatic brake system model is shown in Fig. (**4**). It is mainly composed of air sources, pedal signals, series dual-chamber brake valves, relay valves and brake chambers.

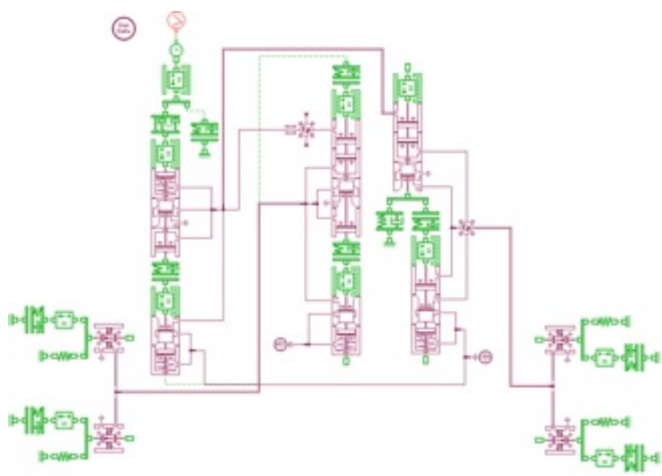


Fig. (4). Pneumatic brake system model.

In the actual working condition, the rated working pressure of braking system is 800 kPa. Independent air tanks supply air for anterior and posterior brake chamber. Therefore two constant pressure sources, which pressure is 800kPa and temperature is 20 °C, are used as the braking system air supply. Driver makes the brake valve open by brake pedal. So a pedal signal for brake valve braking is necessary. Pedal maximum rated pressure is 2800N. It reaches the maximum value within 0.2s and remains unchanged, make brake pressure output stably [8]. When there is no pedal force signals, brake valves and relay valves are closed. No compressed air is in the brake circuit. When braking, pedal force is applied to brake valves, brake valves open, compressed air can get into the brake circuit and eventually reach the brake chamber to brake the wheel; when the brake is released, pedal force disappears. Brake valves, relay valves and brake chamber push the piston and valve moving back under the effect of each reset spring. Air ports are closed and air circuit is cut off.

Simulation time is 10s and step size is 0.01. The pneumatic braking system response curve can be get (Fig. **5**). Dotted lines stand for brake valve response curve, solid lines stand for brake chamber response curve. Fig. (**5**) shows that when braking system reaches 800 kPa stable output time is 0.39s. When braking is keeping, pressure is stable and has no fluctuation. Brake rescission time is 0.536s. During braking, the anterior brake chamber release time is faster than posterior brake chamber's. Specific results are shown in Table **4**.

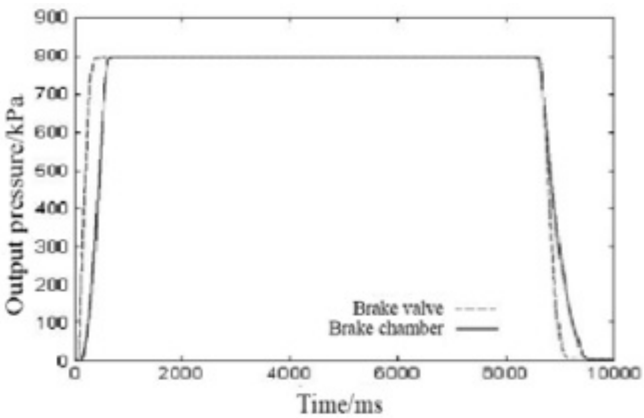


Fig. (5). Brake system response characteristics simulation results.

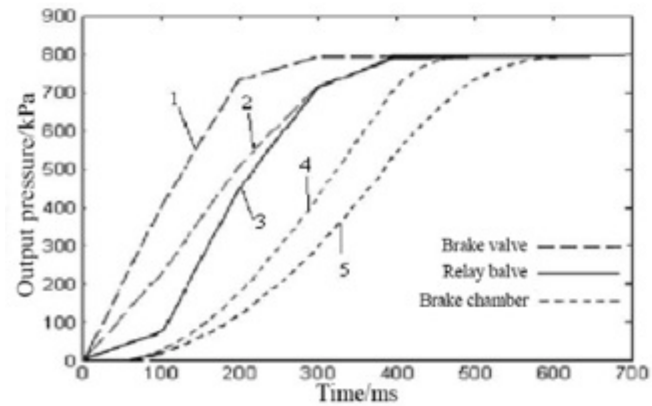
Table 4. Pneumatic brake system dynamic response characteristics results.

Name	Response Time/s	Pressure Maintenance/s	Release Time/s
Front wheel	0.39	8.00	0.536
Rear wheel	0.45	7.90	0.542
Pedal	0.20	8.00	0.200

3.5. Output Coordination Time

The output coordinate time of pneumatic braking system, is the time from the brake pedal being pressed to each brake parts beginning to have an output pressure. Fig. (**6**) shows the dynamic response curves of brake valve relay valve and brake chamber in the system. Brake valve responses instantly at almost 0 s, relay valve must be opened only when control air pressure reaches a certain value, the brake chamber starts output air pressure at 0.06 s. The results are shown in Table **5**.

It can be concluded that pneumatic brake system dynamic characteristics are not only related to dynamic characteristics of brake components, but also related to the output transfer between brake components. Therefore, in order to guarantee the fast and stable output of brake system, it should not only to analyze the dynamic characteristics of the brake components, but also analyze pressure transmission time between brake valve→relay valve, brake valve→anterior brake, relay valve→posterior brake chamber.



1-brake valve upper cavity;2- brake valve lower cavity; 3-relay valve;4-anterior brake chamber;5-posterior brake chamber

Fig. (6) Brake components output coordination time simulation results.

Table 5. Brake system output coordination time.

Name	Response Time/s
Brake valve - relay valve	0.03
Brake valve -anterior brake chamber	0.06
Relay valve -posterior brake chamber	0.04

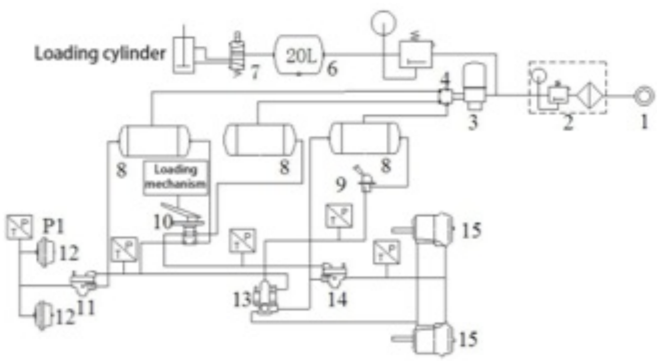
4. DESIGN OF PNEUMATIC BRAKE TEST-BED

In order to verify the correctness of the model, the pneumatic brake system test-bed has been designed. The brake system and its key components can be tested. By comparing experimental results and simulation results, the accuracy of the model can be further verified.

4.1. Overall Design of Pneumatic Circuit

In order to achieve the goal of fast loading within 0.2 s, meanwhile no damage to the products, the loading mode of applying low friction cylinder simulates fast braking situation. The high speed data acquisition technology is used to obtain circuit pressure values. Brake system response time is calculated by feature point extraction. When fast braking, air source aerates cylinder, cylinder pushes the rod moving fast, to achieve the goal of fast brake. The loading speed can be up to 1000 mm/s, and braking time is less than 0.2 s. It can meet the dynamic loading requirements. Design of pneumatic circuit is shown in Fig. (**7**).

The air source provides air pressure for master valve, relay valve, spring braking chamber, meanwhile provides quick cylinder of air source power. The air from air source goes through two-linked-parts which filters out the moisture and impurities and finally deposits the air in the air reservoir. Pneumatic circuit uses ø 12 plastic pipes.



1-air source; 2- two-linked-parts; 3-dryer; 4- four circuit protection valve; 5-pressure reducing valve; 6-20 L air tank; 7- two-position five-way valve; 8-30 L air tank; 9- hand valve; 10-master valve; 11- front axle relay valve; 12-brake chamber; 13- differential relay valve ; 14- rear axle relay valve;15-spring brake chamber

Fig. (7). Pneumatic circuit designs.

4.2. Design of Data Acquisition and Control System

Data acquisition and control system is shown in Fig. (**8**). It is made up of data acquisition module and control execution module. Data acquisition module is composed of AI (Analog Input) channels, displacement sensors, pressure sensors and data acquisition cards. Control execution module is composed of two-position five-way valves, pneumatic control valves, electric proportional valves, power boards, etc.

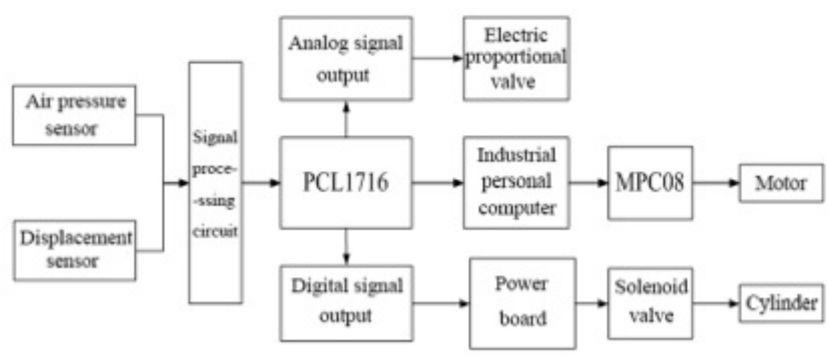


Fig. (8). Acquisition system schematic diagram.

In data acquisition module, the 16-bit, 250 kS/s sampling frequency, multifunction PCI bus data acquisition card was chosen. Its working sampling frequency is 5 kS/s for each channel. According to the requirements of vehicle working pressure of 800 kPa, the pressure sensor with a range of 0-16 bar, a precision class of 0.25 was chosen. The maximum stroke of master valve push rod is less than 20 mm. So the linear displacement sensors were selected at input terminal. In control execution module, industrial personal computer outputs analog quantity by AO (Analog Output) channel, controls the electric proportional valves, achieves accurate control of the brake air pressure. By setting the DO (Digital Output), digital signals through power plate control solenoid valve. The loading of cylinder and the on or off of the pneumatic circuit can be controlled. The TLE6228 chip of Infineon Company is adopted on power plate, the response speed is 5-20 us. It can meet the requirements of the experiment.

5. PNEUMATIC BRAKE SYSTEM SIMULATION EXPERIMENTAL VERIFICATION

5.1. Dynamic Characteristics Experimental Verification

According to China national standard GB12676-1999 and GB7258-2012, the brake system with the standard pneumatic is experimented. By comparing the experimental results with the numerical simulation results (Figs. **6**, **9**), the results are shown in Table **6**. There are two main differences. First, the simulation output pressure responses at 0 s. But in reality, pedal push rod is not in fully contacting with the brake valve. There is some empty travel. It has nothing to do with brake system internal structure. Second, brake chamber simulation curve is smooth, and test curve is fluctuant. It is because the rubber bowl compressive deformation causes the change in diameter. Thus the output is affected. It can be seen that by comparing the results. The simulation results are in agreement with the experimental results, the model is verified.

5.2. Output Compatibility Experimental Verification

Simulation and experimental results are shown in Figs. (**7**, **10**), and the output coordinate time results are showed in Table **7**. From the simulation results it can be seen that it

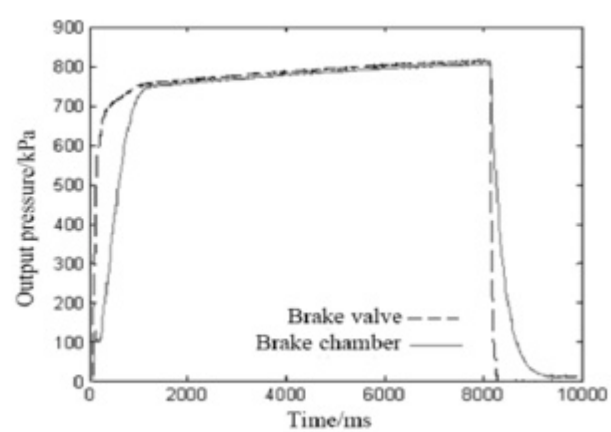
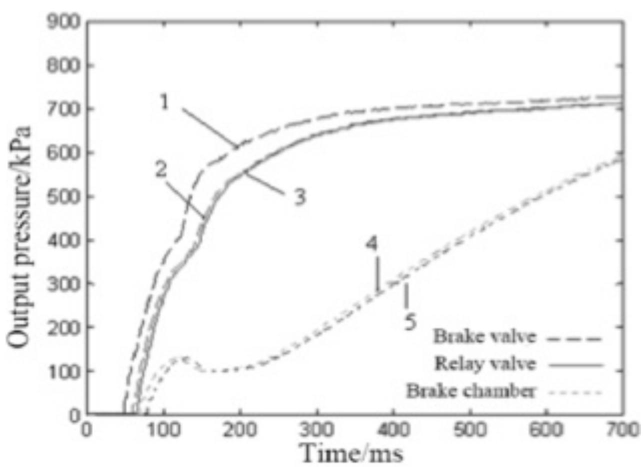


Fig. (9). Braking system response characteristic test results.

takes 0.06 s from the brake valve to anterior brake chamber. But from relay valve to posterior brake chamber, pressure build-up time is only about 0.04 s. Relay valve plays a role in accelerating the inflation process, speeds up the posterior brake chambers response speed, make the brake system response and output brake pressure rapidly. From the experimental results the same conclusion can also be obtained.

Table 6. Brake system dynamic characteristic simulation and test results.

Name	Simulation Results/s	Test Results/s
Response time /s	0.39	0.55
Release time /s	0.536	0.623
Working air pressure /kPa	800	800



1- brake valve upper cavity; 2- brake valve lower cavity; 3-relay valve;4-anterior brake chamber; 5-posterior brake chamber

Fig. (10). Coordination of response output.

Table 7. Output coordinate time simulation results and experimental results.

Name	Simulation Results/s	Test Results/s
brake valve - relay valve	0.03	0.04
brake valve -anterior brake chamber	0.06	0.07
relay valve -posterior brake chamber	0.04	0.03

CONCLUSION

The pneumatic brake system model was setup and a pneumatic brake system simulation test-bed was designed. Dynamic characteristics simulation analysis and experimental tests were done with the pneumatic brake system. By comparison, the simulation results are in good consistent with the experimental results and meet the demand of pneumatic brake system. The simulation model is proved correct. Using the simulation model can analyze the dynamic characteristics and output coordination of the braking system. When the brake is released, the compressed air needs returning to the brake parts exhaust ports through the pneumatic circuit. This will lengthen the brake rescission time. So the quick release valve is added in the brake system to speed up the air discharge. The pneumatic brake system's errors occurred in the brake chamber, mainly because of the rubber diaphragm deformation. So it is concluded that the rubber diaphragm elastic coefficient is an important cause of braking system response delay.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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