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Design and Experimental Evaluation of PID Controller for Digital Electro-Pneumatic Cabin Pressure Control System

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Abstract: The performance of the designed digital electro-pneumatic cabin pressure control system for the cabin pressure schedule of transport aircraft is investigated. For the purpose of this study, an experimental setup consisting of a simulated hermetic cabin and altitude simulation chamber is configured for cabin pressure control system operation. A series of experimental tests are executed to evaluate the performance of the cabin pressure control system. The parameters of the PID controller are optimized. In the optimization process, the variation regularity of the rate of cabin pressure change under various conditions is considered. An approach to prioritize the control of the rate of change of cabin pressure based on the flight status model is proposed and verified experimentally. The experimental results indicate that the proposed approach can be adopted for the designed digital electro-pneumatic cabin pressure control system to obtain a better cabin pressure schedule and rate of cabin pressure change.

Key words: cabin; pressure control; digital electro-pneumatic; PID controller

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0 Introduction

The cabin pressure control system (CPCS) controls the cabin pressure and pressurization rate to protect the passengers and the airplane. Since pneumatically driven systems have many distinct characteristics, such as energy-saving, cleanliness, a simple structure and operation, and high efficiency, and are suitable for working in a harsh environment, they have been extensively used for many years in cabin pressure control systems[1,2]. Recently, the appearance and development of electro-pneumatic proportional components have advanced pneumatic control techniques beyond the restrictions of point-to-point control. Electro-pneumatic proportional control components can convert an analog electrical input signal into outlet flow or pressure. Therefore, they can dramatically simplify pneumatic and electric circuits.

In the past few years, several researchers have devoted their investigations to modeling the electro-pneumatic cabin pressure control system[3,4]. Other studies have mainly focused on the digital proportional, integral, and derivative (PID) control strategy for the electro-pneumatic cabin pressure control system[5-9]. The current trend to develop an improved electro-pneumatic cabin pressure control system with good performances in terms of safety, stability, and accuracy requires investigation to find the optimum parameters of a PID controller. This paper investigates the stability and dynamic performance of a digital electro-pneumatic cabin pressure control system with the PID control method. For the purpose of this study, an experimental setup is configured

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for cabin pressure control system operation. The PID controller, which is connected in a microcomputer together with a data acquisition card, is implemented. A series of tests are conducted to verify the controller′s performance for particular situations that are relevant to the aircraft′s cabin pressure control system behavior.

1 Cabin Pressure Control System Model

Fig. 1 shows the arrangement of the digital electro-pneumatic cabin pressure control system, which is composed of a digital controller, outflow valve, and cabin. As illustrated in Fig. 1, two absolute pressure sensors are used to monitor the atmospheric pressure and cabin pressure, respectively. The cabin pressure and its rate of change are set by the cabin pressure selector. The required target for the actuator is calculated with PID according to the atmospheric pressure from the air data computer and a given cabin pressure schedule. D/A drives torque motor deflection to transform the opening of the outflow valve, which in turn controls the pressure, excess pressure, and rate of cabin pressure change in real time.

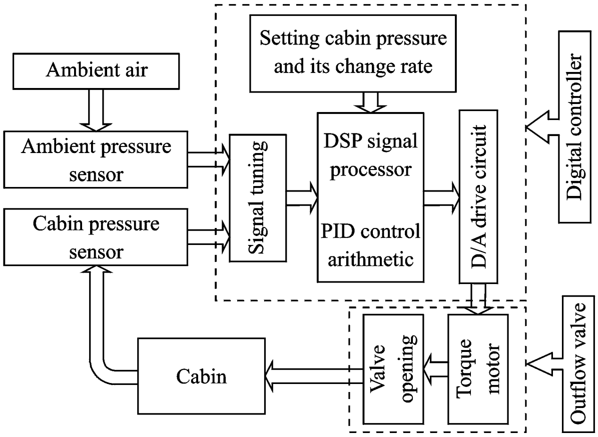

Fig. 1 Arrangement of digital electro-pneumatic cabin pressure control system

Fig. 2 shows a schematic diagram of the outflow valve. The valve action is driven by the gravity of the moving part, preload of the spring, and differential pressure between the cabin pressure and cavity pressure. Compared with a purely pneumatic system, the digital pneumatic actuator has a digital signal regulator. This regulator consists of four elements: two nozzles with an air inlet from the cabin and an exhaust outlet to the atmosphere, a torque motor, and a triangle block. The torque motor dives the triangle block to change the nozzles′ cross-sectional area, which controls the flux of air. Consequently, the valve opening is controlled by differential pressure on the diaphragm for controlling the pressure and rate of pressure change in the cabin.

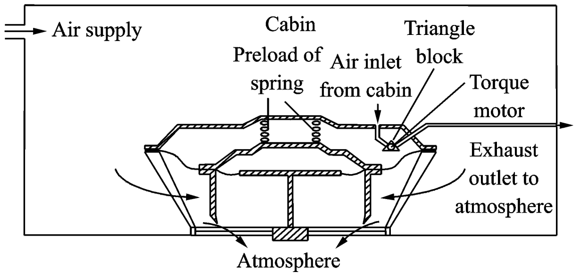

Fig. 2 Structure of outflow valve

2 Experiment

Fig. 3 shows the setup of the experiments. The core of the system is a simulated hermetic cabin. The simulated hermetic cabin and the digital controller are connected with a communications cable. This digital controller receives the simulated hermetic cabin pressure, the atmospheric pressure, and differential pressure signals. Before the activation of the controller, the rule set and associated membership functions in a precompiled format are sent to it. The atmospheric environment is simulated by a high-altitude simulation cabin[4,5], which simulates the atmospheric pressure while climbing and descending during flight. The atmospheric pressure is controlled by the openings of the gulp valve and the outflow valve. Two pressure transducers are used to check the pressure in the hermetic cabin and the pressure in the high-altitude simulation cabin, respectively. An air mass flow sensor is used to measure the flow rate at the inlet of the hermetic cabin. A vacuum pump expels the air of the high-altitude simulation cabin through the outflow valve. The installation of the outflow valve is shown in Fig. 4.

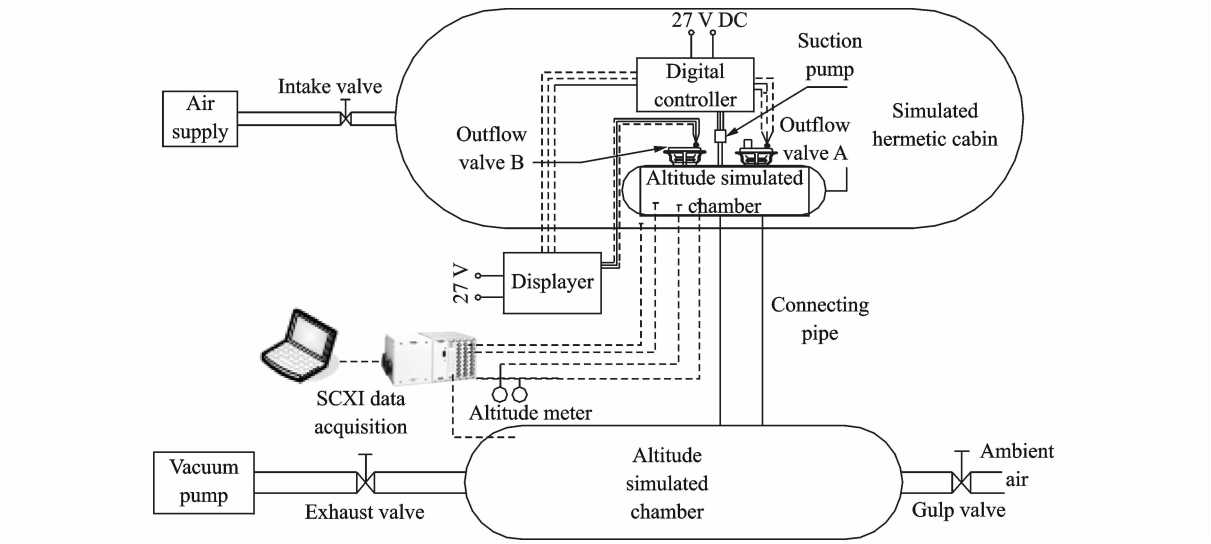

Fig. 3 Experimental setup of cabin pressure control

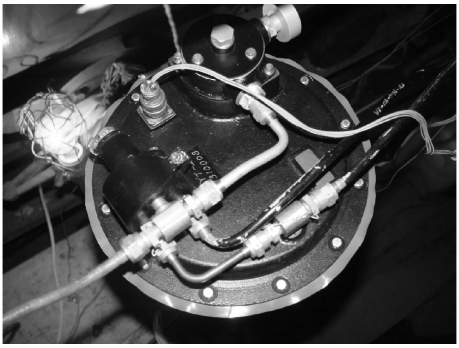

Fig. 4 Installation of outflow valve

The measurement and control system is built for data gathering and controlling the pressures of the hermetic cabin and the high-altitude simulation cabin based on the virtual instruments. A data acquisition and control board named SCXI-1600 is used in the system. SCXI-1600 has an accuracy of 16 bit and a rate of up to 200 kb/s. The current signal of the pressure sensors is sent to a PC via the SCXI-1102 conditioning module and SCXI-1303 terminal board. The output of the control signals computed and filtered from an analog device is transmitted by SCXI-1124 and the SCXI-1325 terminal board. The measurement and control system hardware structure is shown in Fig. 5. The test rig is automated with LabVIEW software to ensure the timing and sequence of events are precise and repeatable. Through LabVIEW, the acquisition and control codes are developed. Using the LabVIEW software provided by the MATLAB script node, the acquisition and control codes can directly call Fuzzy Logic Toolbox of MATLAB via LabVIEW to design the fuzzy control rule and correction.

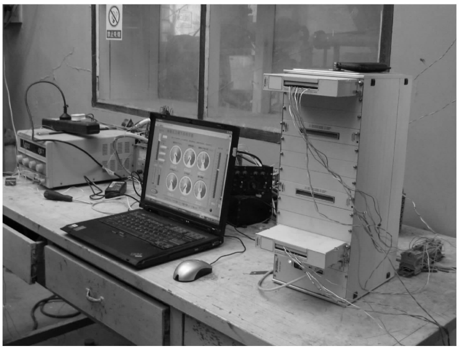

Fig. 5 Measurement and control system hardware structure

Controlling the pressure of the high-altitude simulation cabin is very difficult during testing. This is associated with the performance of the cabin pressure control system being tested. It is difficult for the automatic control of pressure to meet the functioning requirements when the per-

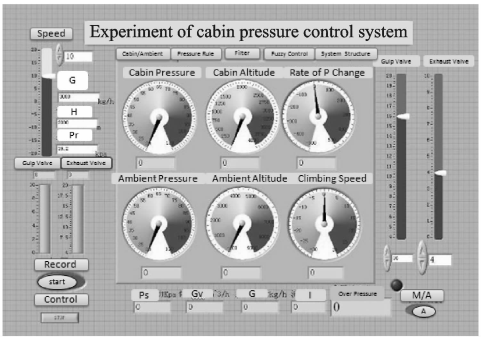

Fig. 6 Application interface

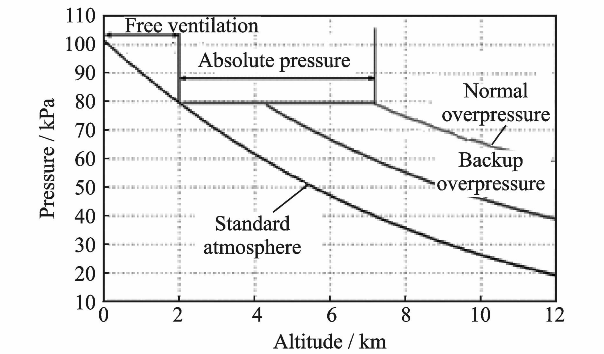

Fig. 7 Cabin pressure schedule of transport aircraft

formance of the cabin pressure control system being tested is unstable. This is because the variation of the outflow valve opening causes air to flow into the high-altitude simulation cabin, which results in rapid change in a short period of time, showing that the change of cabin pressure is larger, and even leads to the coupling resonance of the two control systems and breakdown of the test unit. Therefore, manual intervention is necessary during the early stage of experiment, and the automatic control is activated when the tested pressure control system is relatively stable.

3 Experimental Results

A series of tests are executed to evaluate the performance of the cabin pressure control system for transport aircraft. A cabin pressure schedule of transport aircraft is shown in Fig. 7. The cabin pressure is divided into three zones: free ventilation, absolute pressure, and overpressure within the flight altitude range. Based on these pressure data, the PID control parameters can be found by systematically adjusting their values to obtain the best permitting ones.

In this section, a series of tests are performed in order to validate the performance of the digital electro-pneumatic cabin pressure control system for a given flight status. Two main requirements should be satisfied:

(1) The pressure of the simulated hermetic cabin is controlled to follow the cabin pressure schedule of transport aircraft during climbing and diving.

(2) The rate of the simulated hermetic cabin pressure change under climbing and diving conditions is controlled.

According to the PID algorithm, the controller output signal consists of three terms

$$u = K_p\left(e + \frac{1}{T_i}\int e\mathrm{d}t + T_d\frac{\mathrm{d}e}{\mathrm{d}t}\right) \tag{1}$$

where e represents the deviation signal of the control parameter, K_p the proportional gain, T_i the integral time constant, and T_d the differentiating time constant. In the paper, u is the output current signal of the torque motor and e the pressure difference signal. The pressure signal is gathered 10 times per second by using anti-pulse-interfere median filtering. The nonlinear partial differential equations are converted to the incremental type in the calculation of PID[10]

$$\Delta u(n) = K_p\Delta u_p(n) + K_i\Delta u_i(n) + K_d\Delta u_d(n) \tag{2}$$

$$u(n) = u(n-1) + \Delta u(n) \tag{3}$$

where K_p, K_i, and K_d are the constants. The values for $u(n)$ and $\Delta u(n)$ are the set upper and lower limits according to the practical system.

The test considers a setting pressure value of the absolute pressure region for three cabin altitudes: 90 kPa for 1 km, 80 kPa for 2 km, and 70 kPa for 3 km, and the supply airflow rate is 3 000 kg/h. The PID control parameters are set to $K_p=3$, $K_i=0.5$, and $K_d=2$ along with a sampling period of 1 s. The valve reaches the maximum opening to ensure free ventilation when the value of ambient pressure is larger than that of the setting pressure. The experimental data for the 1 km working condition are listed here to illustrate the problems during the control process. Fig. 8 shows the experimental response of the cabin pressure for climbing within the free ventilation zone and absolute pressure zone for the 1 km working condition. Similar to the purely pneumatic cabin pressure control system, the cabin pressure curve overshoots down from the free ventilation zone to the absolute pressure zone. This is because the valve is not closed promptly at the appropriate location. The drive current shows that the torque motor opens the valve faster than it closes the valve for the same $\Delta u(n)$; Thus, the pressurized process forms faster than the decompression process. Clearly, the pressure control system cannot work within the absolute pressure zone.

In order to solve the problems, the judgment of setting pressure is added into the program (See Fig. 8). The input current of the torque motor is decreased before the ambient pressure reaches the setting pressure, so that the valve is gradually closed to reduce the overshoot of the setting pressure point.

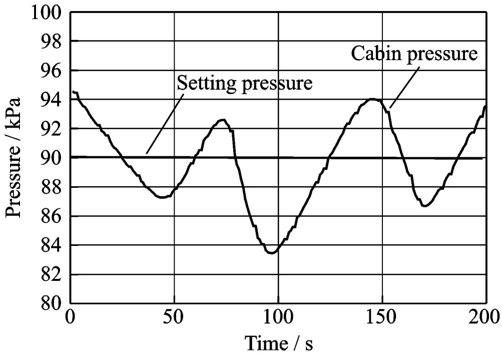

Fig. 8 Experimental response of cabin pressure with $K_p=3$, $K_i=0.5$, and $K_d=2$

In order to suppress the amplitude of cabin pressure oscillation, the integral term of the PID algorithm is separated as follows:

- When $|e(n)|>1$ kPa, let $K_i=0$ and choose the PID method.
- When $|e(n)|<1$ kPa, use the PID method, and the sampling period selected is 3 s.

The experimental results for the responses for 1 km with the optimized PID algorithm are shown in Fig. 9.

It can be seen from Fig. 9 that the overshoot is suppressed after the point starts to adjust the pressure. By using integral separation and increasing the control cycle, the pressure in the absolute pressure zone becomes (90±2) kPa, which basically meets the pressure control target even though decompression is still faster than pressurization in the curve.

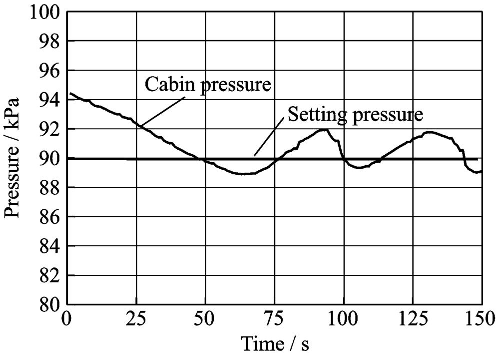

Fig. 9 Experimental response of cabin pressure with optimized PID algorithm

Figs. 10, 11 show the complete curves of the cabin pressure and its rate of change with altitude during the aircraft climbing process. In Fig. 10, the cabin pressure basically conforms to the cabin pressure schedule of the transport aircraft, but significant fluctuations still exist in the whole process. As shown in Fig. 11, the speed of pressurization is greater than $+40$ Pa/s, and the speed of decompression is greater than -100 Pa/s. Actually, similar problems appear under 2 km and 3 km working conditions. Therefore, further tuning of the parameters of the PID controller according to the operating characteristics of the system is necessary.

It turns out to be very difficult to achieve accurate and stable control merely by tuning the PID parameters. The operating characteristics of the cabin pressure control system need to be further analyzed.

According to the operating principle of the system, overpressure is the power source of outflow valve actuation. The change of overpressure is the main interference of the system when the supply airflow is constant. For a given cabin pressure schedule, the cabin overpressure increases as the altitude increases within the absolute

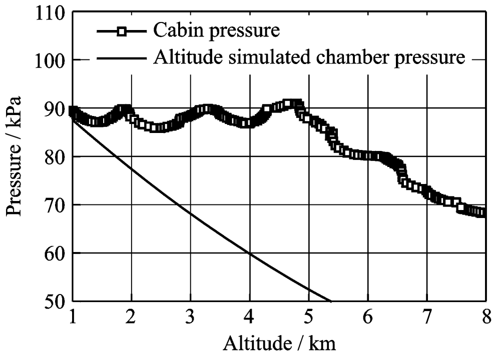

Fig. 10 Cabin pressure response curves with flight altitude during climbing (1 km)

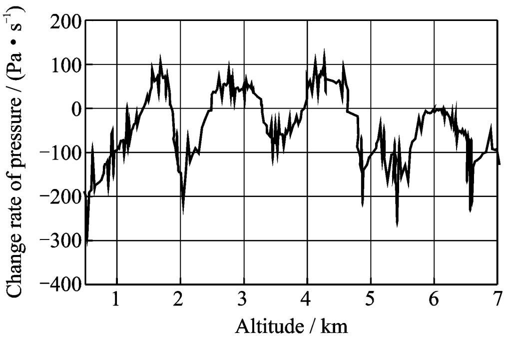

Fig. 11 Rate of cabin pressure change with flight altitude during climbing

pressure zone when the aircraft climbs and the opposite occurs when the aircraft dives.

In order to keep the exhaust flow constant, it is necessary to decrease the opening of the outflow valve when the overpressure increases for climbing. The speed of pressurization probably exceeds the design standard during the process. The judgment of the rate of cabin pressure change needs to be considered preferentially to maintain the rate of cabin pressure change within a specified range. Specifically, when the rate of change is greater than some typical values, the operating of the valve should be retarded or even stopped. The operating of the outflow valve depends on the displacement of the block driven by a motor. The electric current used to drive the corresponding valve opening should be decreased as the overpressure increases. For the diving and cruising process, a similar analysis should be conducted.

According to the above analysis, some modifications are made to the digital PID control program:

(1) Determining the flight status of the aircraft (climbing/diving/cruising).

(2) Adjusting the PID parameters based on the flight status to follow the change of overpressure.

(3) Judging the rate of cabin pressure change in the decompression and pressurization processes to keep the rate of cabin pressure change within a specified range preferentially.

The results of the experimental verification based on the above proposed control method are shown in Figs. 12—19. Specially, Figs. 18, 19 show the results of the backup status when the backup overpressure is 19. 6 kPa.

As can be seen from the experimental results, the developed digital electro-pneumatic cabin pressure control system can match the given cabin pressure schedule. Meanwhile, the experimental results indicate that the rate of cabin pressure change can be controlled effectively with the proposed approach.

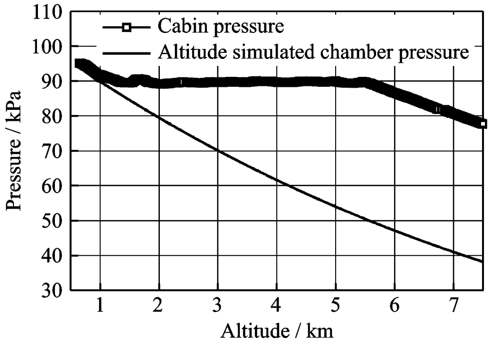

Fig. 12 Cabin pressure responses during climbing for the proposed model (1 km)

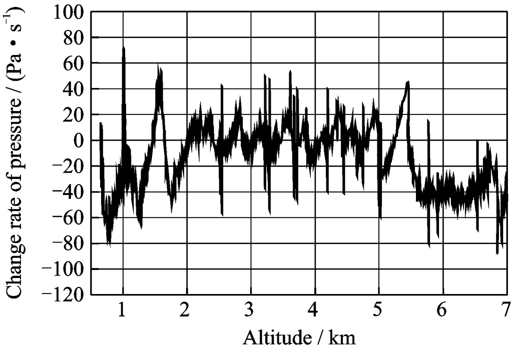

Fig. 13 Rate of cabin pressure change during climbing for the proposed model (1 km)

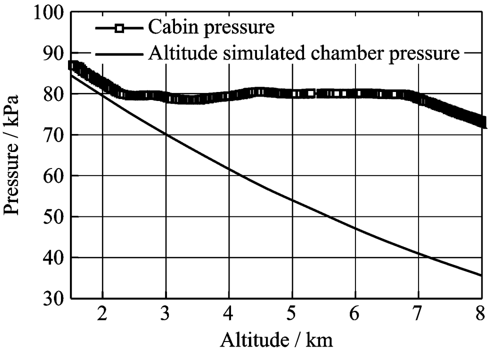

Fig. 14 Cabin pressure responses during climbing for the proposed model (2 km)

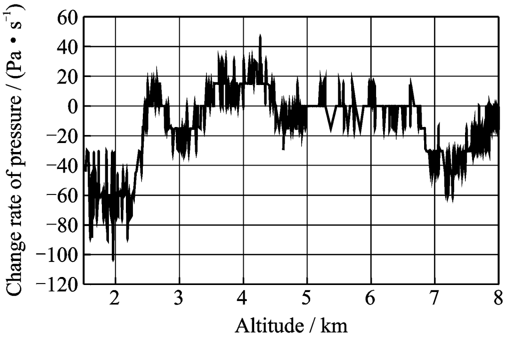

Fig. 15 Rate of cabin pressure change during climbing for the proposed model (2 km)

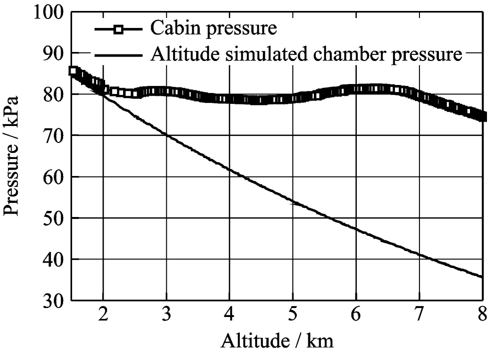

Fig. 16 Cabin pressure responses during diving for the proposed model (2 km)

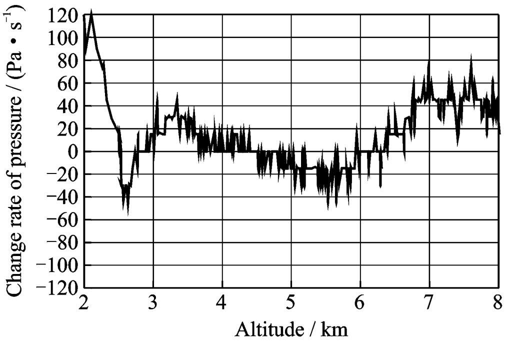

Fig. 17 Rate of cabin pressure change during diving for the proposed model (2 km)

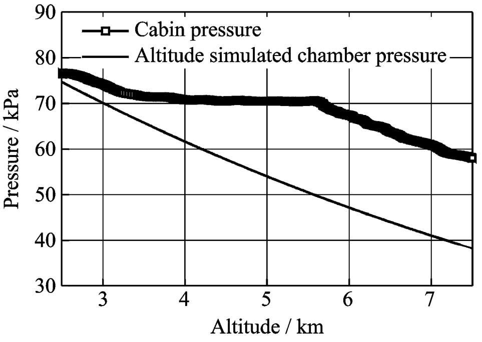

Fig. 18 Cabin pressure responses during climbing for the proposed model (3 km, backup overpressure)

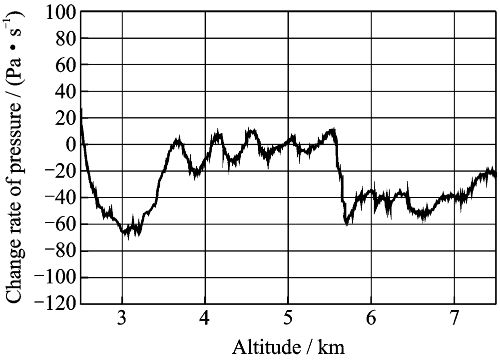

Fig. 19 Rate of cabin pressure change during diving for the proposed model (3 km, backup overpressure)

4 Conclusions

An approach to prioritize the control of the rate of change of cabin pressure based on the flight status model for a digital electro-pneumatic cabin pressure control system is presented in order to improve control performance during aircraft climbing and diving. Experimental evaluation of the pressure controller is carried out for a digital electro-pneumatic cabin pressure control system, and the results show the controller can work effectively and stably to control the cabin pressure rate of change to fulfill the requirement of human physical comfort.

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