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RESEARCH ON PNEUMATIC POSITION CONTROL SYSTEM BASED ON A NEWLY-DEVELOPED ROTARY ACTUATOR WITH A BUILT-IN BRAKE

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ABSTRACT

In this paper, a newly developed pneumatic rotary actuator is introduced, which is specially designed for angular position control. The actuator incorporates a built-in air brake and an angular displacement sensor. The basic behavior of the brake is tested. On this basis, for angular position control some control systems are proposed. The first system is the on-off valve-based position control system, which has the advantages of simple control algorithm, easy implementation and lower cost. The second system is the proportional valve position control system with simple PID algorithm, which can reach a required positioning accuracy but with a lower stiffness against disturbance. The third system is the proportional valve position control system with a composite control strategy of PID combined with brake aided positioning, which can reach the same positioning accuracy and no overshoot with disturbance takes place, as compared with the simple PID.

KEY WORDS

Pneumatic rotary actuator; Position control; Brake; Proportional valve; PID algorithm

INTRODUCTION

Currently, there are mainly two approaches to implement the pneumatic position control. One is the pneumatic position servo system, in which the proportional /servo valve or on-off valve is used as a control device. This type of system has not been widely used due to its high cost and low stiffness with the effect of the compressibility of air. Another is the positioning system, in which the pneumatic actuator with brake is used. For this system, the positioning stiffness is higher, but the positioning accuracy is lower. Therefore, it is expected that a new control mode that combines the merits of the above-mentioned control systems would be researched and developed [1-3]. Because of the difficulty in the structure, there is not a market product of pneumatic rotary actuators with brake providing for use.

In this paper, the structure of a newly developed pneumatic rotary actuator with a brake (abbreviated as RAB) is introduced. For further control purpose, the basic property of the air brake is studied. On this basis, the angular position control of the new rotary actuator is demonstrated.

THE STRUCTURE AND OPERATION MECHANISM OF THE PNEUMATIC ROTARY ACTUATOR WITH A BRAKE

Structure of the Rotary Actuator with a Brake (RAB)

As shown in Fig. 1, the developed RAB consists of three components: pneumatic rotary actuator, brake unit and angular position detection unit. The photo of the RAB prototype is shown in Fig.2.

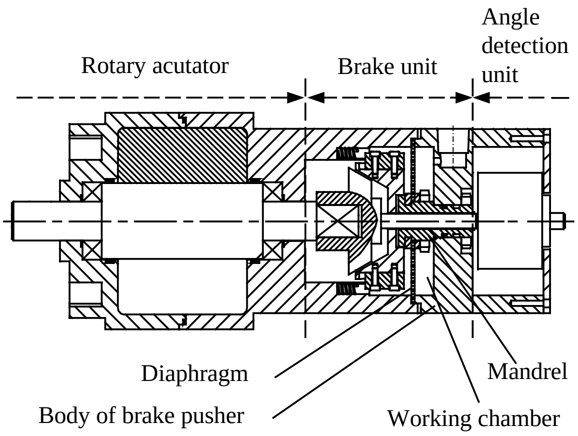

Fig. 1 Scheme of the RAB structure

Fig. 2 Photo of the RAB prototype

In the RAB, the component of the rotary actuator is similar to the structure of an ordinary pneumatic rotary actuator of vane-type. A rotary potentiometer is used as an angular displacement sensor, which is mounted in the component of angular position detection unit. The brake unit consists of a brake operator and a brake pusher. In following sections, the structure and operation mechanism of the brake unit will be introduced in detail.

Structure and Operation Mechanism of the Brake Pusher

As shown in Fig.1, the component of the pusher consists of the diaphragm, the hollow mandrel and the body of the brake pusher. The diaphragm is fixed on the mandrel and the mandrel is fixed on the body of the brake pusher. The diaphragm, the mandrel and the body of the brake pusher form the working chamber. When pressurized air is charged into the working chamber, the deformation of the diaphragm is produced and a pushing force is exerted on the tapered disc B in the brake operator. If the air is discharged from the working chamber, the deformation of the diaphragm is removed and the pushing force is also removed.

In order to measure the shaft speed, a rotary potentiometer should be connected to the shaft of the tapered disc A. So the mandrel is made hollow.

Structure and Operation Mechanism of the Brake Operator

As shown in Fig. 3, the brake operator mainly consists of the tapered disc A, the tapered disc B and the body of the brake operator. The tapered disc A is fixed on the rotary shaft and rotates together with the shaft. The tapered disc B is mounted in the body of the brake operator and its rotation is restricted only with the permission of linear motion along the direction of the shaft.

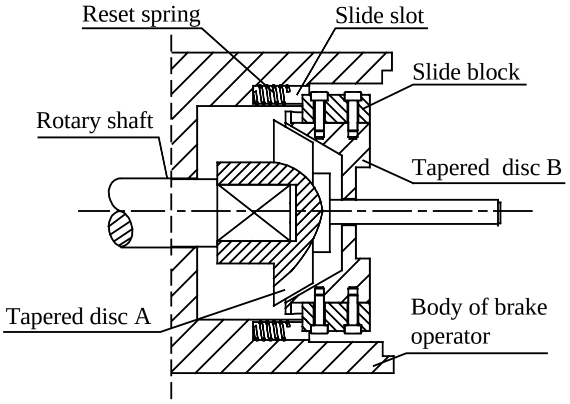

Fig. 3 Scheme of the brake operator

From Fig. 3, the operation mechanism can be illustrated. When tapered disc B is pushed by the diaphragm in the pusher component (see Fig. 1), it moves along the axial direction and exerts a force on the tapered disc A, so as to generate a friction torque on the shaft through the tapered disc A. The shaft rotation will be reduced or ceased with the torque. When the pushing force of the diaphragm is removed, the diaphragm will restore its initial state and the tapered disc B will return its initial position with the action of the reset springs.

HOLDING TORQUE OF THE BRAKE

Theoretical Analysis of the Holding Torque of the Brake

(1) Holding torque of the brake operator

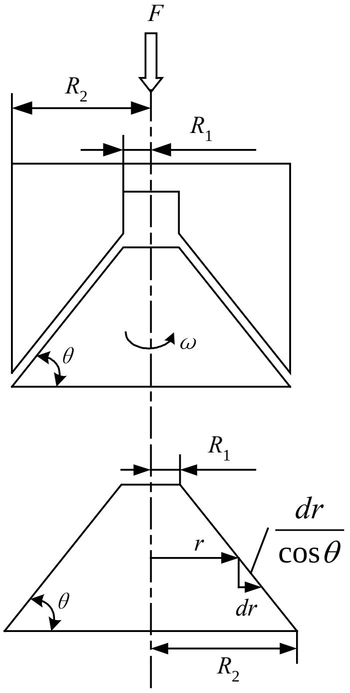

Fig. 4 Friction torque analysis of the tapered disc

The holding torque of the brake operator is the friction torque on the two conical surfaces of the tapered discs. According to Fig. 4, the pressure vertically exerted on the conical surface can be expressed as

$$p = \frac{F}{\pi({R_2}^2 - {R_1}^2)} \tag{1}$$

Therefore, the friction torque on the conical surfaces exerted by the pushing force F is derived as

$$\begin{aligned} M &= \int_{R_1}^{R_2} \frac{\mu p}{\cos\theta} 2\pi r^2 dr \\ &= \frac{2\mu F(R_1^2 + R_1 R_2 + R_2^2)}{3\cos\theta(R_1 + R_2)} \end{aligned} \tag{2}$$

Where θ is inclined angle of the conical surface, R_1 is top radius of the tapered disc A, R_2 is bottom radius of the tapered disc A, F is axial pushing force and μ is friction coefficient.

Eq. (2) indicates that the holding torque of the brake operator is proportional to the axial pushing force.

(2) Pushing Force of the Brake Pusher

The pushing force exerted by the brake pusher comes from the deformation of the ring diaphragm with the compressed air. The force analysis of the deformation of the diaphragm with small deflection is shown in Fig.5.

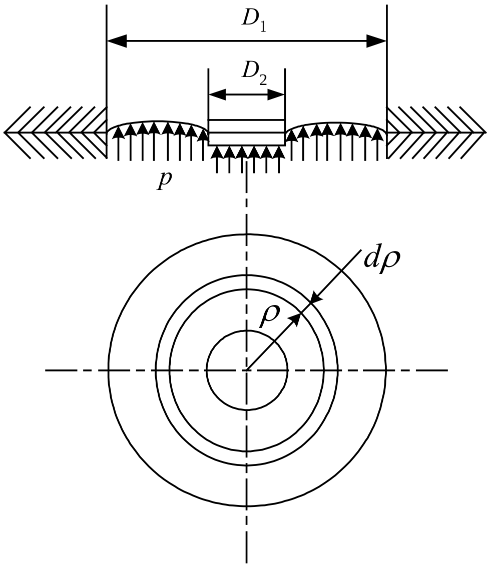

Fig. 5 Force analysis of the diaphragm

According to Fig.5, the pushing force produced by the diaphragm can be derived as

$$\begin{aligned} F &= \int_{D_2/2}^{D_1/2} p \frac{D_1 - 2\rho}{D_2 - 2\rho} 2\pi\rho \, d\rho \\ &= p\frac{\pi}{12}(D_1^2 + D_1 D_2 - 2D_2^2) \end{aligned} \tag{3}$$

Where D_1 is diameter of the working chamber, D_2 is diameter of the mandrel and p is air pressure in the working chamber.

Eq. (3) indicates that the pushing force produced by the diaphragm is proportional to the pressure in the working chamber. From Eq. (2) and (3), it can be seen that the holding torque of the brake is proportional to the pressure in the working chamber.

Experiments of the Holding Torque of the Brake

Experiments are carried out to measure the relation of the holding torque and the supply pressure. The measured curve is shown in Fig.6. From Fig. 6, it can be seen that the holding torque is approximately proportional to the supply pressure in the working chamber. This indicates that the experimental result is coincident with preceding theoretical analysis.

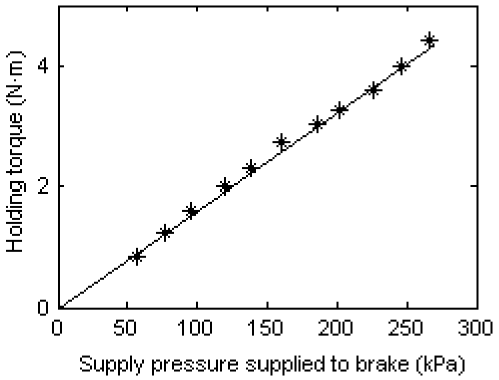

Fig. 6 Holding torque versus supply pressure in the brake working chamber

POSITION CONTROL OF THE RAB

RAB Position control system based on on-off valve

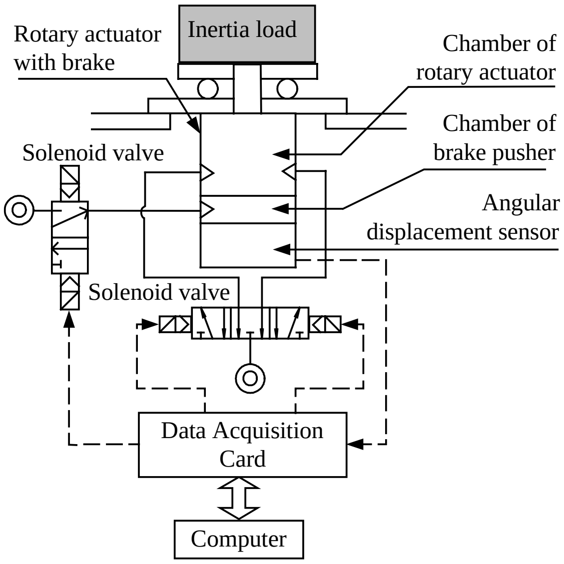

Fig. 7 Schematic constitution of the position control system based on on-off valve

As shown in Fig. 7, an on-off valve-based position control system is built up, in which ordinary solenoid valves are used for controlling the rotary actuator and the brake. Considering the response time of the solenoid valve and the braking distance of the brake, the actuator will continue to rotate for a certain time interval after the stop signal is sent. The rotating angular distance of the actuator within this time interval is defined as overrun-distance.

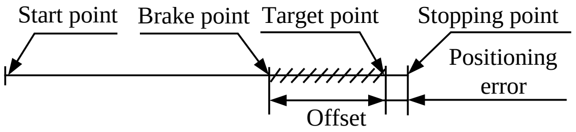

Fig. 8 Schematic of the positioning process with offset compensation method

Therefore to remove the practical influence on the accurate positioning, an offset compensation method is proposed. From Fig. 8, the principle of the offset compensation method can be illustrated. When the actuator rotates to certain position ahead of the target point, the stop signal is sent in advance. Thus the system will stop near the target point with less positioning error. Experiments are conducted with different loads and target positions. The measured positioning errors with 5 kg load are listed in Table 1.

Table 1 Positioning error measured with 5 kg load

Speed(°/s)	224			418			739		
Target position (°)	90	150	240	90	150	240	90	150	240
Positioning error (°)	0.26	0.25	0.48	0.78	0.91	0.02	1.18	0.13	0.33

Experimental results show that the positioning error is within the range of ±2° if the target rotary angle is beyond 90°. However if the target rotary angle is smaller than 90°, the speed of the actuator is unsteady in its running and the compensation value is difficult to be given. Experimental data involving this part has not listed yet. To improve the control performance with the smaller rotary angle, further research work is needed.

It can be seen that the position control system based on on-off valve has advantages of simple control algorithm, easy implementation and lower cost.

Position control system based on proportional pressure valve

In proportional valve-based position control system, two proportional pressure valves are used for controlling the pressure in the chambers of the rotary actuator. A solenoid valve is used for controlling the brake, as shown in Fig. 9.

To improve the performance, another control mode is explored. For this control mode, a composite control strategy of PID algorithm combined with brake aided positioning is adopted. As we know, the actuator would be decreased to a lower speed when it approaches the target points with PID control mode and could acquire a higher positioning accuracy. In this case if the actuator rotates at a low speed, the effect of the brake could be sufficiently obtained. This feature can be utilized to form the basis of the composite control strategy, i.e., PID control algorithm combined the method of brake aided positioning.

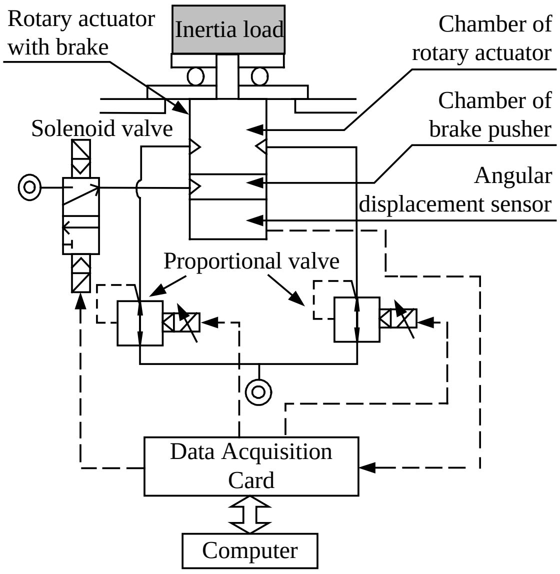

Fig. 9 Scheme of the position control system based on proportional pressure valve

We can describe the positioning strategy in detail. First, PID control algorithm is used for controlling the motion of the rotary actuator. Then, as the system enters into quasi steady state, the brake is operated to make the system into the steady state quickly, at the same time, PID algorithm is ceased and the proportional valves are switched off. The quasi steady state is defined as the state in which the error is kept within the desired precision range during a time interval.

The step response of the system with external force disturbance is shown in Fig. 10. From Fig. 10, it can be seen that with PID control the positioning precision is higher but there exists larger overshoot with disturbance. Adopting PID control strategy combined with brake aided positioning, the same positioning accuracy can be obtained and no overshoot with disturbance takes place, as compared with simple PID algorithm.

CONLUSIONS

For meeting the practical requirement of a pneumatic rotary actuator with brake in industrial automation systems, a new pneumatic rotary actuator with brake (RAB) is developed and introduced. Based on this RAB, some control systems are presented and tested. The first one is the on-off valve-based position control system, which has the advantages of simple control algorithm, easy implementation and lower cost but with the default of low accuracy. To increase the positioning accuracy, another proportional valve-based position control system with simple PID algorithm is presented, which can reach a required positioning accuracy but with a lower stiffness against disturbance. To improve the performance against disturbance, the third system is presented, which is the proportional valve position control system with a composite control strategy of PID combined with brake aided positioning. Experiments have shown that the system with the composite control strategy can reach the same positioning accuracy and no overshoot with disturbance takes place, as compared with simple PID algorithm.

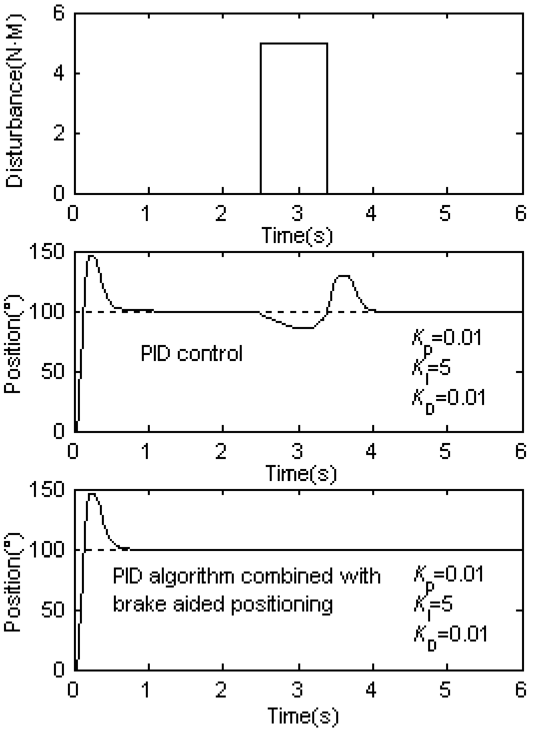

Fig. 10 Step response with external disturbance

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