Research on Stepless Force Control Strategy of Multistage Force Cylinder Based on Simulation

Zhongfu Bao* and Dejiang Zeng
Guangdong Mechanical & Electrical Polytechnic, Guangzhou, China

*Corresponding author e-mail: bzfjixie@163.com

Abstract. Aiming at the problem that the output force of the cylinder is small, this paper studies a method based on the simulation technology to obtain the larger output force and realize the stepless control of the output force. Through the simulation analysis, it can be seen that the system can achieve a more stable output force control when the system damping is large. There will be a certain amount of impact when each stage of cylinder is started.

1. Introduction
Pneumatic system has many advantages, such as sensitive response, convenient control and low cost, so it is widely used in industrial automation production. However, the pneumatic system uses compressed air as the power source. In the field of industrial automation, the pressure of the air source is generally less than 1MPa, so the output force of the cylinder is generally small. This limits the use of the pneumatic system in some cases with large load.

How to improve the output force of pneumatic system is also a hot issue in the field of pneumatic transmission. In this paper, based on the simulation, we study the characteristics of a system which can obtain a large output force by connecting multiple cylinders in series.

2. Multistage force cylinder structure
The multi-stage force cylinder is to connect the cylinders in series, so that the output force of multiple cylinders forms a resultant force, as shown in Figure 1.

Figure 1. Multistage force cylinder structure
From the characteristics of the components, the first stage cylinder is a single piston rod cylinder, and the connected cylinder is a double piston rod cylinder. The input port of the first several stages of the cylinder is controlled by a two position three-way valve, and the output port is directly connected with the atmosphere. The last stage cylinder is controlled by two position five way valve. By connecting the corresponding reversing valve, the output of multi-stage force can be realized. If the reversing valve of each stage is driven by proportional electromagnet, stepless control can be realized.

3. **Principle of stepless force control**

The system adopts the hierarchical control method, and takes the cylinder output force as the control object. The force sensor is used to collect the actual output force feedback value of the cylinder, and the error between the preset value and the actual value is used as the control signal to drive the opening of the proportional directional valve. Each stage is controlled by a proportional valve.

In order to realize the continuous increase of cylinder output force, the three proportional valves should be opened in turn according to certain control laws. The proportional valve of the first stage is directly driven by the error signal, so it directly opens to let the pressure air enter the first stage cylinder, so that the system obtains a lower output force. When the error signal exceeds the threshold \( a \), the proportional valve of the second stage will open. At this time, two cylinders in the system are filled with pressure air, and the system can obtain higher output force. When the error signal further exceeds the threshold \( b \), the proportional valve of the third stage will open. At this time, all three cylinders in the system are filled with pressure air, and the system can obtain the highest output force. The control law of the system is shown in Figure 2.

![Figure 2. Principle of stepless force control](image)

4. **Build simulation model**

The simulation analysis of pneumatic system is based on AMESim, which provides a platform for simulation modeling and analysis in many fields through modular component library. By using the components of the pneumatic system library and the pneumatic component design library, the model of three cylinders in series can be built. The first two cylinders are controlled by two position three-way reversing valve, and the last one is controlled by two position four-way reversing valve. By using the components of the mechanical library, the load of the pneumatic system can be built. The load
is simplified as a mass block, which is connected to the ground through spring damping. By using the components of the signal library, the model of the controller can be built. The controller has the functions of input, output and calculation of analog quantity and digital quantity. The actual output force of the cylinder is read by the force sensor, and the error signal is obtained by subtracting the signal from the predetermined signal, and then the threshold value of each proportional valve is determined. The whole simulation model is shown in Figure 3.

![Simulation model of stepless control for multi-stage force cylinder.](image)

Figure 3. Simulation model of stepless control for multi-stage force cylinder.

5. Analysis of simulation results

5.1. System stability analysis

In order to improve the stability of the pneumatic system, the spring and damping elements are used to connect the load and the ground. Among them, damping has a direct impact on the stability of the system. Batch analysis can be used to understand the influence of different damping on the system. The values of damping C are 20 and 100 respectively, and the output force of cylinder is analyzed and compared. The predetermined output force and the output forces of the three systems are shown in Figure 4 and Figure 5 respectively.

![Graphs showing output force comparison.](image)

Figure 4. Output force when damping is 20

Figure 5. Output force when damping is 100
By comparing these figures, we can see that the overall trend of cylinder output force is consistent with the booking requirements. It can be seen from Figure 4 that when the damping is 20, the stability of the system is poor, and after about 25 seconds, the output force starts to oscillate continuously, mainly because the start of the second stage cylinder brings the excitation to the system. Due to the low damping of the system, the energy of vibration cannot be consumed in a short time. After about 75 seconds, the system amplitude increases again, which is caused by the start of the third stage cylinder. It can be seen from Figure 5 that when the damping is 100, system stability greatly improved. Only at the moment when the second and third stage cylinders start, small amplitude vibration occurs, and the vibration lasts for about 5 seconds. As this study focuses on the realization of stepless control of output force, the selection of system parameters should be as stable as possible. Therefore, in the subsequent analysis, the system damping value is 100.

5.2. System dynamic characteristics
This paper mainly analyzes the dynamic characteristics of the system from the speed and acceleration of the cylinder piston rod movement. It can be seen from the analysis in Figure 6 that from 0s to 10s, when the cylinder is just connected with pressure air, due to insufficient pressure and system inertia, the piston rod speed of the cylinder starts to accelerate slowly from 0. From 10 seconds to 20 seconds, because of the small displacement of the previous piston rod, the pressure in the cylinder piston cavity rises rapidly, and the speed starts to rise abruptly. The rapid operation of the piston rod will cause the sudden increase of the volume of the piston cavity, the pressure drop and the speed drop. When the second stage cylinder starts in 21 seconds, the speed steps up. At 40 seconds, because the valves of the first two stages are closed, the speed steps down and there is a vibration, lasting for about 5 seconds. When the third stage cylinder starts in 70 seconds, the speed oscillates greatly, lasting for about 15 seconds. It can be seen from Figure 7 that when the system starts and stops, the acceleration of the cylinder piston rod will vibrate, especially the third stage cylinder.

From the above analysis, it can be seen that when the system is started at all levels of cylinders, there will be impact and vibration, but it will not last, so the whole system can meet the industrial production requirements of general accuracy.

5.3. Control signals of proportional valves at all levels
By analyzing the operation of each stage proportional valve and cylinder, we can know the working condition of the whole system. For the valve, the control signal is analyzed, and for the cylinder, the inlet pressure is analyzed.

It can be seen from the analysis in Figure 8 that the first stage proportional valve starts to open in 0 seconds and fully opens in about 30 seconds. In the first 20 seconds, the speed of the spool movement
has an obvious acceleration process from low speed to high speed, and in the last 10 seconds, the spool movement shows the characteristics of linear movement. It can be seen from the analysis in Figure 9 that under the influence of the movement law of the valve core, the inlet pressure of the first stage cylinder also shows the law of accelerating rise in the first 20 seconds, and gradually stabilizes at 7 bar after 20 seconds. According to the analysis, the first stage cylinder starts to run from static, and the cylinder output force is generally stable.

![Figure 8. Control signal of the first stage valve](image1)

![Figure 9. Inlet pressure of the first stage cylinder](image2)

According to the analysis in Figure 10, the second stage proportional valve starts to open from about 21 seconds, and the opening moment is relatively stable. When the load stops at the 40th second, there is a small vibration, which is mainly because the force sensor also feeds back the cylinder pressure vibration to the proportional electromagnet. After the 60th second, the valve is loaded again, and the valve core is accelerated to open after small vibration. At about 70 seconds, a large amplitude of vibration occurs, which is mainly due to the interference of the third stage cylinder starting to the system pressure. It can be seen from the analysis of Figure 11 that the inlet pressure of the second stage cylinder shows a law of accelerating rise in the first 20 seconds, and when the load stops in the 40th second, there is a small vibration and it is maintained at 5bar. After the 60th second, it was loaded again, and the pressure rose to 7bar after about 10 seconds. At 70 seconds, due to the interference of the third stage cylinder, there was a large vibration. After about 10 seconds of shock, the pressure continues to increase linearly. It can be seen from the analysis that the change of loading will cause small vibration of the system, and the starting of the third stage cylinder will have a certain impact on the system.

![Figure 10. Control signal of the second stage valve](image3)

![Figure 11. Inlet pressure of the second stage cylinder](image4)
It can be seen from the analysis in Figure 12 that the third stage proportional valve starts to open from about 70 seconds, and a relatively obvious vibration occurs as soon as it is opened. After about 10 seconds of shock, the valve core gradually opens again. It can be seen from the analysis in Figure 13 that in the first 70 seconds, under the influence of the operation of the first two stages of the cylinder, there is a negative pressure at the inlet of the third stage of the cylinder. After 70 seconds of opening, the inlet pressure has a step, and after a small fluctuation, it is stable at 7 bar. Through the analysis, it can be seen that the starting of the third stage cylinder will have a certain impact on the system.

6. Conclusion
In order to solve the problem that the output force of the cylinder is small, this paper studies a method based on the simulation technology to obtain the larger output force and realize the stepless control of the output force. Through the simulation analysis, it can be seen that the system can achieve a more stable output force control when the system damping is large. A certain amount of impact will be produced when each stage of cylinder is started, which needs to be used together with the shock absorber in the precise operation occasions.

Acknowledgments
This work was financially supported by Characteristic and innovative projects of universities in Guangdong Province (Project No.:2018GKTSCX113).

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