Construction of contact force prediction model for cushion cylinder based on simulation and response surface method

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

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

Abstract. Cushion cylinder is often used to alleviate collision in pneumatic manipulators. The pneumatic cushion circuit is a complex system, so it is difficult to calculate the contact force accurately. In order to solve this problem, the virtual experiment is carried out by digital simulation based on experimental design and response surface method, and the contact force prediction model of cushion cylinder is obtained by analyzing the experimental data.

1. Introduction
Pneumatic transmission is widely used in industrial automation because of its sensitivity, rapidity, environmental protection and easy control. Pneumatic manipulator is a typical pneumatic automation equipment, as shown in Figure 1. Usually, the pneumatic manipulator takes the cylinder as the power component, and realizes linear motion with the guide and support components. Cylinders are usually positioned by setting blocks at the starting and end points, which are mostly used for assembly operations with low requirements of precision. As the collision is inevitable when the block is positioned, it is necessary to equip the cylinder cushion device. At present, the design of cylinder cushion device mostly relies on experience and on-site debugging, which is inefficient and has poor reliability.

In this paper, the dynamic characteristics of a double piston rod cylinder as cushion cylinder are studied based on AMESim simulation analysis, which provides a basis for the design of cushion device of pneumatic manipulator.

Figure 1. Cushion cylinder in Manipulator
2. Analysis of cushioning pneumatic circuit of double piston rod cylinder

The pneumatic system using double piston rod cylinder as cushion cylinder is shown in Figure 2. The component numbered 7 is the cushion cylinder. It is floating connected in the air passage. The fixed block set at the upper and lower end of the arm will collide with the piston rod of the buffer cylinder, which acts as an air spring to exert reverse force on the arm to achieve the deceleration process. The cushioning cylinder can adjust the cushioning effect by adjusting the opening of the regulating valve.

3. Simulation modeling based on AMESim

3.1. Construction of simulation model

This paper focuses on the cushioning process of cylinder 7 to cylinder 5 in Figure 2. SMC brand cylinders are selected as simulation models. The model of cylinder 5 for up and down operation of manipulator is CA2KG50-300, and the model of cylinder 7 for buffer is CG1KWUN20-100. The simulation model can be built based on the pneumatic component library, pneumatic component design library, mechanical library and related components in signal library provided by AMESim. The simulation model is shown in Figure 3.
The simulation time is set to 3 seconds, and the calculation step is 0.0001 seconds. After the simulation calculation, the diagrams of the related results can be obtained.

3.2. Analysis of Simulation Results
In order to verify the correctness of the simulation model, observational simulation is used to analyze the relevant parameters, and to analyze whether the variation law is consistent with the engineering experience.

After the solenoid valve is powered on for 0.5 seconds, the piston rod of the main cylinder extends rapidly, and the stroke reaches 200 mm in 0.85 seconds. By observing the clearance curve, it can be seen that the clearance has reached 0 at this time, that is, the end of the piston rod of the cylinder has contacted the piston rod of the buffer cylinder and pushed the buffer cylinder forward together, as shown in Figure 4.

The main cylinder starts to decelerate under the action of cushioning cylinder resistance and reaches steady state in about 1.4s, as shown in Figure 5.

Combined with engineering experience, the above simulation analysis conclusions are reasonable, so as to verify the correctness of the simulation model.

![Figure 4. Comparison of Piston Rod Displacement](image)

![Figure 5. Comparison of Piston Rod Speed](image)
4. Constructed Prediction Model Based on Response Surface

4.1. Principle of Response Surface
Response surface design (RSD) is an effective method to establish the relationship between test indexes and continuous variables through a small amount of experimental data. Its basic idea is to approximate a polynomial model with explicit expression in a small area to express a complex unknown function relationship. This method is based on experimental design and mathematical statistics. It not only considers the random error of experiment, but also calculates easily. It is an effective means to solve the problem [6].

In order to investigate the coupling between variables, a complete second-order response surface model with cross terms is adopted.

\[
y(x) = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i=1}^{k} \alpha_{ii} x_i^2 + \sum_{i<j}^{k} \alpha_{ij} x_i x_j + \epsilon
\]

\(k\) —— Number of Design Variables;
\(x_i\) —— Design Variables;
\(\alpha_i, \alpha_{ii}, \alpha_{ij}\) —— Undetermined coefficients of polynomials;
\(\epsilon\) —— error

After \(n\) experiments, the response surface model can be expressed as equation (2).

\[
Y = XA + \epsilon = \bar{Y} + \epsilon
\]

\[
Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, X = \begin{bmatrix} 1 & x_{i1} & \cdots & x_{i1} \\ 1 & x_{i2} & \cdots & x_{i2} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{in} & \cdots & x_{in} \end{bmatrix}, A = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix}, \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}, i = 1, 2, \ldots, n
\]

\(Y\) —— AMESIM simulation value
\(\bar{Y}\) —— Response Surface Approximation Function Value
\(\epsilon\) —— Fitting error

The parameters of quadratic polynomial can be estimated by least square method.

\[
L = \sum \epsilon_j^2 = (Y -XA)^T (Y -XA)
\]

Finding the Extremum from the Extremum Theorem of Calculus

\[
\hat{a} = (X^T X)^{-1} X^T Y
\]

4.2. Design of Experiments
Central composite design is the most commonly used second-order response surface experimental design method. This method is the mainstream second-order response surface experimental design method. It combines the traditional interpolation node distribution with full or partial factor design, and can provide more information with as few experimental times as possible[7].

According to engineering experience, throttle diameter affects gas flow, load quality directly affects inertia load, action force and action time in cushioning process, and is related to stroke of main cylinder and cushion cylinder and piston area. Therefore, choosing throttle diameter, load mass, stroke ratio of
main cylinder to cushion cylinder and piston area ratio, four variables are recorded as x1, x2, x3, x4. The experimental design is shown in Table 1.

| variables | -2 | -1 | 0 | 1 | 2 |
|-----------|----|----|---|---|---|
| x1/mm     | 1  | 3  | 5 | 7 | 9 |
| x2/kg     | 10 | 20 | 30| 40| 50|
| x3/%      | 0.1| 0.2| 0.3| 0.4| 0.5|
| x4/%      | 0.1| 0.2| 0.3| 0.4| 0.5|

According to the experimental points, AMESIM is used to carry out simulation analysis and record each simulation data. Through the experimental data, the response surface model can be obtained and expressed in quadratic form as formula (5).

\[ Y = XA^TX \]

\[ X = [1, x_1, x_2, x_3, x_4] \]

\[
\begin{bmatrix}
241.093 & 0.349549 & -2.24468 & -397.487 & -58.6132 \\
0.349549 & 0.197088 & 0.032079 & -4.71047 & -4.40525 \\
-2.24468 & 0.032079 & 0.013755 & 4.40961 & -0.103869 \\
-397.487 & -4.71047 & 4.40961 & 741.689 & 61.8417 \\
-58.6132 & -4.40525 & -0.103869 & 61.8417 & 249.043
\end{bmatrix}
\]

4.3. Analysis of Experimental Data
Firstly, the main influencing factors of contact force are determined. Through Pareto diagrams, the influence of variables and coupling terms on contact force can be queried, as shown in Figure 6. From the diagram, it can be seen that the influence of cylinder load quality on contact force is the greatest, and its proportion is more than 20%. The influence of cylinder length ratio on contact force is also significant, and the influence proportion is close to 20%.

In the design process of practical engineering, the load quality and length of cylinder are determined by working conditions. The contact force can only be adjusted by changing the size of damping hole, cylinder length ratio and piston area ratio. Therefore, the relationship between quality and these three variables and contact force is mainly determined.

As shown in Figure 7, when the cylinder load mass is below 30KG, the contact force decreases with the increase of the cylinder length ratio. When the length ratio is about 0.4-0.5, the contact force is the smallest. When the load mass is above 30KG, the contact force is parabolic with the cylinder length ratio. When the length ratio is between 0.2 and 0.3, the contact force is the smallest.

As shown in Figure 8, the contact force is always positively correlated with the area ratio regardless of the load quality of the cylinder. Therefore, in order to reduce the contact force, the area ratio can be as small as possible.

As shown in Figure 9, when the cylinder load is below 30KG, the contact force decreases with the increase of the damping hole, and the contact force is the smallest when the ratio is about 8-9mm. When the load mass is above 30KG, the contact force shows a parabolic relationship with the ratio of the size of the damping hole. When the length ratio is about 4-5mm, the contact force is the smallest.
Figure 6. Pareto Diagram

Figure 7. Response Surface

Figure 8. Response Surface
5. Conclusion
Aiming at the problem of cushioning cylinder contact force in pneumatic system, the prediction equation is constructed by using digital simulation and response surface method. The responses of four variables, i.e. the ratio of contact force to cylinder length, the ratio of piston area, load mass and the diameter of damping hole, are also analyzed in detail. The research methods and conclusions in this paper can be used for reference in the design of related pneumatic systems.

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