Experimental Study on the Nonlinear Characteristics of the Mechanism Model of the Control Valve

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Abstract. Pneumatic control valve is a nonlinear electromechanical system with the mechanics, electronics, pneumatics and hydraulics, there is a totally different working mode of aeration and exhaust in any working point, which has typical nonlinear characteristics. Based on the established nonlinear dynamic mechanism model of the pneumatic control valve, the gain and time constant of diffident working point, dead zone and backlash in the rising and falling process and other nonlinear characteristics of the mechanism model are studied and analyzed in this paper through the qualitative analysis and quantitative calculation, which lays the foundation for the research of modeling, control and fault diagnosis.

Introduction

Through a great deal of previous experimental study, a complete nonlinear dynamic mechanism model of pneumatic control valve named Control Valve Model is established. Based on the work flow and principle of the pneumatic valve, the model is established by modularization thinking, which mainly includes three modules, that is intelligent electrical positioner module, pneumatic actuator module and valve body module, and each module also has several internal sub modules.

The module structure diagram of Control Valve Model is shown in Fig. 1.

![Figure 1. Simulation model structure diagram of ControlValveModel.](image)

As shown in the above diagram, the work flow of the mechanism model of pneumatic control valve is as follows. Firstly, the given control signal of valve position SP (4-20mA standard current signal) is transmitted to the intelligent positioner. Secondly, the intelligent positioner transforms the current signal to the backpressure signal of nozzle flapper by internal E/P module, and the volume booster module in intelligent positioner transforms the backpressure signal to gas mass flow signal inflow into air chamber of pneumatic actuator module. Finally, the gas flow changes the air chamber pressure, which leads the film to move and pushes the valve stem move, and then the valve displacement is generated. The functional diagram of mechanism model is shown in Fig. 2.
Study on Gain and Time Constant

Experiment Design.

Gain \( K \) refers to the ratio of the output signal difference and input signal difference when the output signal is stable. In the mechanism model, the gain \( K \) of different operating points is:

\[
K = \frac{PV}{OP}.
\]

Where represents the difference of valve position in stable state, represents the difference of control signal OP.

Time constant refers to the time course of the transition reaction. It refers to the time need to reach \( 1/e \) of the maximum value of the physical quantity. For example, in the step response of the first order system, time constant is the time that output response from zero to the \( 1/e \) of the maximum needed.

Because the gain and time constant of different operating points of the mechanism model need to be studied, the control signal must be set in valid range. And the valve stem can be from 0% to 100% valve position, thus every operating point can be obtained during the operation of valve stem. To this end, this experiment uses step signal as the input control signal and the step control signal OP increases from 34 to 39 and increments by 1. Each step lasts 60 seconds and the sampling frequency is 50HZ. The concrete experimental block diagram is shown in Fig. 3.

Experimental Result Analysis

In Fig. 4, the red dashed line represents the control signal OP, which increases from 34 to 39; The blue solid line represents the valve position corresponding to control signal, which starts from 0% to 100%; The abscissa represents time, 50 sampling points represent 1 second; The ordinate represents control signal OP and the valve position PV. Details of the place A is shown in Fig. 5.
In Fig. 5, when the mechanism model in open-loop simulation, the response of the step test is approximate to first order dynamics, and control signal OP is not limited to the range in this step process, which means the valve position is also not limited.

The corresponding unit step response $C(t)$ of the first order system is:

$$c(t) = k \cdot (1 - e^{-\frac{t}{T}}) \quad (t \geq 0)$$  \hspace{1cm} (1)

When $t=T$, put it into the formula (1), we can obtain that. So when to get the time constant $T$ of system with unlimited range, we can first get the steady-state value of the output response, then calculate $63.2\%$ of the steady-state value and find the corresponding position in the response curve, after that we can find the corresponding time of this position, which is the time constant $T$ of the system.

**Step Control Signal OP: 35→36**

From Fig. 6, from point A to point B corresponds to the change of step control signal OP, so; Point C is the starting point of the valve position, point D is the stable point of valve position, so the ordinate difference between point C and point D is the change of valve position, so, and the gain $K$ of this working point is:

$$K = \frac{DV}{30} = \frac{21.99}{1} = 21.99$$

Point A is the jump point of control signal and point C is the starting point of the valve position response, so the time difference between these two points is the delay.

The sampling frequency is 50HZ, so the delay is:

$$\theta = \frac{60.21 - 60.00}{50} = 0.42s$$

To get the time constant of the working point, firstly we should find the $63.2\%$ of point C and point D, where, which is the point E in Fig. 6. The abscissa difference between point E and point C (that is, the time difference) is the time constant of this working point. So the constant can be obtained:

$$T = \frac{6277 - 6021}{50} = 5.12s.$$
Step Control Signal OP: 36→37

From Fig. 7, from point A to point B corresponds to the change of step control signal OP, so; Point C is the starting point of the valve position, point D is the stable point of valve position, so the ordinate difference between point C and point D is the change of valve position, so, and the gain K of this working point is: 

\[ K = \frac{\Delta PV}{\Delta OP} = \frac{19.97}{1} = 19.97. \]

Point A is the jump point of control signal and point C is the starting point of the valve position response, so the time difference between these two points is the delay. The sampling frequency is 50HZ, so the delay is: 

\[ \Theta = \frac{9018 - 9000}{50} = 0.36s. \]

To get the time constant of the working point, firstly we should find the 63.2% of point C and point D, where, which is the point E in Fig. 7. The abscissa difference between point E and point C (that is, the time difference) is the time constant of this working point. So the constant can be obtained: 

\[ \tau = \frac{9018 - 9000}{60} = 5.84s. \]

Step Control Signal OP: 37→38

From Fig. 8, from point A to point B corresponds to the change of step control signal OP, so; Point C is the starting point of the valve position, point D is the stable point of valve position, so the ordinate difference between point C and point D is the change of valve position, so, and the gain K of this working point is: 

\[ K = \frac{\Delta PV}{\Delta OP} = \frac{23.70}{1} = 23.70. \]

Point A is the jump point of control signal and point C is the starting point of the valve position response, so the time difference between these two points is the delay.

The sampling frequency is 50HZ, so the delay is: 

\[ \Theta = \frac{16508 - 15000}{50} = 0.46. \]

To get the time constant of the working point, firstly we should find the 63.2% of point C and point D, where, which is the point E in Fig. 8. The abscissa difference between point E and point C (that is, the time difference) is the time constant of this working point. So the constant can be obtained: 

\[ \tau = \frac{16508 - 15000}{60} = 6.42s. \]
From the above calculation, the gain and time constant of every working point during the open loop step test of mechanism model can be seen in Table 1.

Table 1. Gain and time constant of each working point of open loop step test.

<table>
<thead>
<tr>
<th>Control signal OP</th>
<th>Gain K</th>
<th>Time constant T(s)</th>
<th>Delay Theta(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35→36</td>
<td>21.99</td>
<td>5.12</td>
<td>0.42</td>
</tr>
<tr>
<td>36→37</td>
<td>19.97</td>
<td>5.84</td>
<td>0.36</td>
</tr>
<tr>
<td>37→38</td>
<td>25.78</td>
<td>6.42</td>
<td>0.48</td>
</tr>
<tr>
<td>Changing range</td>
<td>21.99–25.78</td>
<td>5.12–6.42</td>
<td>0.42–0.48</td>
</tr>
<tr>
<td>Change percentage</td>
<td>17.24%</td>
<td>25.4%</td>
<td>14.3%</td>
</tr>
</tbody>
</table>

Summary: from the experiment results of the open loop step simulation can be seen that the mechanism model of control valve is nonlinear, and the gain, time constant and time delay of different operating points are different. The gain ranges from 22 to 26, the time constant ranges from 5 to 6.5, and the delay of different working points of mechanism model is almost same.

**Study on Dead Zone Characteristics**

**Experiment Design**

The dead zone refers to the finite interval without any detectable change of output when the input changes. The movement direction of valve stem changes as the control signal changes the direction, dead zone exists during this process. Sinusoidal signal is set as the control signal in this simulation for the reason that sinusoidal signal changes its direction at 1/4 cycle, when very easy to observe whether there is a dead zone in mechanism model.

The control signal of mechanism model is \( OP = 35 + 2\sin(\omega t) \), where \( \omega = 2\pi/40 \), period \( T=40s \) and sampling frequency is 50HZ.

Specific control signal is shown in Fig. 9: \( OP = 35 + 2\sin(\omega t) \).

![Figure 9. Sine control signal.](image)

**Experimental Result Analysis**

![Figure 10. Simulation results of sinusoidal signal.](image)
In Fig. 10, the red dashed line represents the control signal OP, the blue solid line represents the valve position PV; The abscissa represents time, 50 sampling points represent 1 second; The ordinate represents control signal OP and the valve position PV. When reaching 1/4 cycle, the control signal changes the direction and from increasing to decreasing. The corresponding response of valve position do not immediately change direction, but to maintain the movement state of former moment, there is a period of steady state. This interval is the dead zone of the mechanism model, the details of the black circle P is shown in 11.

\[
D = -7.3 = C \quad 94.63 = 0.15
\]

**Study on Backlash Characteristics**

**Experiment Design**

The backlash (also called variation) refers to the difference of corresponding output signal in the rising and falling process of the same input signal. The output responses in the rising and falling process should be compared under the condition of same input signal and different input signal, so the experiment designs that the valve starts from 0% position to 100% position and then from 100% position to 0% position. To this end, small amplitude step signal is used as the input signal in this experiment, the step signal OP increases from 33.5 to 30 and increments by 0.5, and then decreases from 39 to 33.5 and the decrements by 0.5. Each step lasts 120 seconds, and the sampling frequency is 50HZ.

**Experimental Result Analysis**
The valve position PV after the step response of the mechanism model entering steady state is used to draw OP&PV table, as shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>OP</th>
<th>PV(%)</th>
<th>OP</th>
<th>PV(%)</th>
<th>OP</th>
<th>PV(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upward phase</td>
<td>33.5</td>
<td>0</td>
<td>34</td>
<td>0</td>
<td>34.5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>16.1</td>
<td>35.5</td>
<td>25.68</td>
<td>35.5</td>
<td>38</td>
</tr>
<tr>
<td>downward phase</td>
<td>46.99</td>
<td>58.23</td>
<td>68.47</td>
<td>80.71</td>
<td>89.4</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>37</td>
<td>37</td>
<td>38</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>46.99</td>
<td>58.23</td>
<td>68.47</td>
<td>80.71</td>
<td>89.4</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>37</td>
<td>37</td>
<td>38</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>57.45</td>
<td>68.7</td>
<td>77.95</td>
<td>90.16</td>
<td>99.6</td>
<td>100</td>
</tr>
</tbody>
</table>

According to the data in Table 2, the small step forward and reverse of the same input value of the steady-state valve position, you can get the mechanism model of the pneumatic control valve simulation results of the OP&PV hysteresis curve as shown in Fig. 14:

**Figure 13. Diagram of small step down phase.**

**Figure 14. OP&PV hysteresis curve.**

Fig. 14. is analyzed: when control signal OP=35.5, the stop point of the valve position in the rising and falling process is respectively point A and point B, there is a obviously gap between A and B, which is the backlash. The backlash =A-B=35.11-25.68=9.43 when OP=35.5; when control signal OP=36, the backlash is the distance between point C and point D, so the backlash =C-D=44.22-33.25=10.97; These two examples show that mechanism model not only has backlash, but also the backlash is not the same for different control signal and different working points.

The difference of valve position between positive and reverse stroke of the same input is mainly the backlash caused by static friction and a small part of sticky of the working point.

In horizontal analysis, point a is in a falling stage, and the control signal OP=36.5; Point B is in the rising stage, and the control signal OP=37; As seen in the figure, the ordinate of point a and point b is very closed, which shows that the response of valve position is approaching and the
difference of the control valve is 0.5; Similarly, point c and point d is the same. The interval which keeps the valve position stable is the backlash, and the dead band is 0.5;

In the last section, the dead band of mechanism model obtained by sine simulation experiment is 0.51, which is almost the same as the result of small step simulation experiment.

The backlash of each control signal (on working state) is shown in Table 3:

<table>
<thead>
<tr>
<th>Control signal SP</th>
<th>34</th>
<th>34.5</th>
<th>35</th>
<th>35.5</th>
<th>36</th>
<th>36.5</th>
<th>37</th>
<th>37.5</th>
<th>38</th>
<th>38.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return difference</td>
<td>5.76</td>
<td>9.15</td>
<td>7.95</td>
<td>9.43</td>
<td>10.97</td>
<td>10.46</td>
<td>10.47</td>
<td>9.48</td>
<td>9.45</td>
<td>10.2</td>
</tr>
</tbody>
</table>

The above table shows that backlash of different control signals or different working points are different.

Conclusions

By the means of qualitative analysis, experimental study and quantitative calculation, this paper in-depth studies the gain and time constant of different working point, dead zone and backlash in the rising and falling process and other nonlinear characteristics of the mechanism model, verify this mechanism model exactly has nonlinear characteristics, and lays the foundation for the research of modeling, control and fault diagnosis. But some nonlinear characteristics are not studied such as interference factors including the reaction force of valve core, fluctuation of gas source pressure, viscosity property of valve stem and so on, these issues need to be further studied in the next stage.

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References


