Mechanism Modeling and Parameter Identification of Mass Flow in a Pneumatic Amplifier

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Abstract. Pneumatic amplifier is common pneumatic accessories in pneumatic control valve gas path system, but also is a necessary component in valve positioner, used to achieve air pressure and power amplification. In this paper, a new type of high efficiency pneumatic amplifier is studied, based on the principle of thermodynamics and fluid mechanics, the mass flow mechanism model of pneumatic amplifier is established, and the parameter identification is carried out, the accuracy of the model is verified by experiments.

Preface

We have built up a complete mechanism model of intelligent positioner and regulator valve, and named ControlValveModel. In this paper, the gas mass flow model in the model is introduced, and the modeling and identification method of equivalent section area model of small hole in gas mass flow module is introduced in detail, finally, a verification experiment is given, to verify the accuracy of the model and the parameter identification of the equivalent section area of the small hole.

Modeling of a complex system, according to function, it can be divided into sub modules with different function, each module can independently accomplish the fixed function. Only need to set the standard interface specification, each sub module can be done by different researchers, finally according to the standard interface specification, the combination of all sub modules into the whole system. Regulator valve and intelligent positioner is a complex system, collecting gas circuit, electric circuit, magnetic circuit, the ControlValveModel model is divided into the intelligent positioner module, pneumatic amplifier module and regulating valve body module. The intelligent positioner module includes PID control module, E/P conversion module, pneumatic amplifier module (The pneumatic amplifier also includes the working state model and the gas mass flow model); Pneumatic amplifier module includes the gas thermodynamic model and the Stem dynamics model; regulating valve body module includes flow model and unbalanced force model.

According to the idea of modular modeling, and the physical structure and working principle of pneumatic control valve, The ControlValveModel module is divided as shown in Fig.1 below:
Figure 1. ControlValveModel simulation model structure diagram.

As shown above, The workflow of ControlValveModel model is: Regulator send valve position control signal SP(0-100, the corresponding valve position 0-100%)to intelligent positioner, intelligent positioner capture the current valve position signal PV(0-100)and operate PID operation with valve position control signal (SP), the result is the driving signal(OP) of the electromagnetic coil of the positioner (Take Yama Take AVP200 series locator as an example, according to the design of its driving circuit, the control current output of the control board is 0-1.16mA, therefore the input current range of the electromagnetic coil of the E/P conversion unit in the model is 0-1.16mA), OP signal is converted into a pressure control signal(Pb) by the E/P conversion module of the positioner. In the end, pressure control signal is converted into gas mass flow by the working state model and the gas mass flow model (needing combined effects of Pb, Ps, p). Gas flow through the pneumatic actuator is changed to the air chamber pressure (The change of air chamber pressure is related to the valve position and the movement speed of the valve stem), pushing film motion under the stem dynamics model (related to the pressure of the gas chamber, the valve stem displacement and the imbalance force), the film push rod, thereby generating valve displacement.

Gas Mass Flow Model

The charge and discharge process of pneumatic amplifier can be equivalent to flow characteristics of a small hole, divided into two states, the state of sonic flow and the state of the subsonic flow, The gas mass flow model is expressed by the following formula:

\[
\begin{align*}
q_m &= 0.04 \frac{P_1}{\sqrt{\Theta_1}} S_e \quad & \text{b} \geq \frac{P_2}{P_1} \quad \text{(sonic flow)} \\
q_m &= q_m^* \left(1 - \left(\frac{P_2}{P_1}\right)^{\frac{1}{2}}\right) \quad & \text{b} < \frac{P_2}{P_1} \leq 1 \quad \text{(subsonic flow)}
\end{align*}
\]
Among, $q^*_{m}$ is gas mass flow rate in sonic flow, $q_{m}$ is gas mass flow rate in subsonic flow, $P_1$ is pressure at the upstream of the small hole, $P_2$ is pressure at the downstream of the small hole, $\theta_1$ is air temperature at the upstream of the small hole, $S_e$ is effective section area of small hole, $b$ is critical pressure ratio, general selection for 0.5283.

Small Hole Equivalent Area Model

In the model of gas mass flow, the effective section of the hole is the effective section of the flow gas from the upstream through the small hole to the downstream, no accurate mathematical expression is used to directly describe the effective section area, and it is difficult to get accurate measurements through specific tools or methods, therefore, a new model is needed for the effective section area of the small holes.

**Experimental Principle.** Pneumatic amplifier can be equivalent to a double seat control valve, a group of air inlet, a group of air-out, both linkage. According to the flow characteristic curve, in the case of valve pressure fixed, the relationship between flow rate and valve position is determined by the shape of the spool. According to the different shape of the spool, they have linear flow characteristics, equal percentage flow characteristics, etc. And valve position is decided by joint force of valve stem, observing pneumatic amplifier equivalent double seat control valve spool, is linear shape, there is reason to suspect that the flow rate is linear with the external force of the valve stem. According to the formula of gas mass flow model in the sonic flow $q^*_{m} = 0.04\left(\frac{P_1}{\sqrt{\theta_1}}\right)S_e$ in the case of the upstream pressure of the small hole is determined, The flow rate is linear with effective section area($S_e$).According to the above two conclusions, it is concluded that the effective section area is linear with the external force of the valve stem. Setting test experiment, verify that the flow rate is linear with the external force.

**Experiment Design.** Experimental objective: To verify the linear relationship between the flow rate and external force of the valve stem in equivalent double seat control valve.

Experimental setup: Pneumatic amplifier divide into intake spool and exhaust spool, the principles and experimental procedures of the inlet and exhaust gas are the same, pneumatic amplifier simplified as shown in Fig.2 double spool structure:

Figure 2. simplified structure diagram of pneumatic amplifier.

Experimental introduction: In the case of upstream pressure ($P_1$) is determined, by giving different pressure control signals ($P_s$), then measure the flow rate ($q^*_{m}$)by flow meter. According to the working state model formula, external force in equivalent valve stem is
As the airflow through the pneumatic component into the atmosphere, $P_{out}=0$. Therefore, each control pressure signal can determine an external force value.

Experimental procedure: 1. Determine air source pressure ($P_{in}$) set a control pressure signal ($P_b$), measuring and recording the mass flow rate of gas ($q_{m}$) under the current control pressure by the flow meter.

Air source pressure remains constant, increasing control pressure, measuring and recording the corresponding gas mass flow until when the control pressure continues to increase, gas mass flow is unchanged.

Change air source pressure, repeat (step 1-3).

**Experimental Result Analysis.** Experiments were carried out under different air pressure conditions (100Kpa, 150Kpa, 200Kpa), gas mass flow with different control pressure signal is recorded, as shown in Table 1.

| $P_{in}$ (100KPa) | $P_{in}$ (150KPa) | $P_{in}$ (200KPa) |
|-------------------|-------------------|-------------------|
| $P_b$ (KPa)       | $q_m$ (kg/s)      | $P_b$ (KPa)       | $q_m$ (kg/s)      | $P_b$ (KPa)       | $q_m$ (kg/s)      |
| 81                | 0                 | 97                | 0                 | 119               | 0                 |
| 82                | 0.3               | 98                | 1.9               | 120               | 1                 |
| 83                | 2.8               | 99                | 2.9               | 121               | 1.6               |
| 84                | 3.9               | 100               | 3.4               | 122               | 2.3               |
| 85                | 4.2               | 101               | 3.9               | 123               | 2.9               |
| 86                | 5.5               | 102               | 4.6               | 124               | 3.4               |
| 87                | 6.2               | 103               | 5.1               | 125               | 4                 |
| 88                | 7                 | 104               | 5.7               | 126               | 4.5               |
| 89                | 7.3               | 105               | 6.3               | 127               | 5.1               |
| 90                | 7.9               | 106               | 7                 | 128               | 5.5               |
| 91                | 8                 | 107               | 7.7               | 129               | 6                 |
| 92                | 8.2               | 108               | 8.2               | 130               | 6.6               |
| 93                | 8.3               | 109               | 8.6               | 131               | 7.6               |
| 94                | 8.3               | 110               | 9                 | 132               | 8.4               |
| 95                | 8.35              | 111               | 9.2               | 133               | 9                 |
| 96                | 8.4               | 112               | 9.35              | 134               | 10.2              |
| 97                | 8.4               | 113               | 9.4               | 135               | 10.6              |
| 98                | 8.5               | 114               | 9.5               | 136               | 10.6              |
| 99                | 8.5               | 115               | 9.5               | 137               | 10.6              |
| 100               | 8.4               | 116               | 9.5               | 138               | 10.6              |

According to the formula $F = P_bS_1 - (P_{out}S_2 + P_{in}(S_2 - S_3))$, diagram can be drawn under different air pressure, the relation between gas mass flow ($q_m$) and external force in equivalent valve stem as shown in Fig.3, Fig. 4, Fig.5 below.
From the above figure, we can draw the following conclusions:

Gas mass flow is proportional to the external force.

When the external force increases to a certain extent, the gas mass flow will not increase.

Under different air source pressure, the ratio of external force to gas mass flow is different.

Using a mathematical formula expression to describe the conclusion:

\[
S_e = \begin{cases} 
\text{Max}, & F \geq \text{Threshold} \\
kF, & F < \text{Threshold} 
\end{cases}
\]
Among, $S_e$ is equivalent section area of the small hole; $\text{Max}$ is the maximum of the equivalent section area of the small hole; $k$ is the ratio coefficient between the equivalent section area and the external force in the same air source pressure; Threshold is the threshold of External force could be increased.

**Parameter Identification of Equivalent Area Model of Small Hole**

Take YAMA TAKE AVP200 series locator as an example, operate open loop experiment of the actual control valve and the simulation control valve model respectively. The input current range of the electromagnetic coil of the E/P conversion unit is 0-1.16mA. Firstly, operate the step test of the preset valve position signal (SP) from 0-100, its corresponding control current signal from 0mA to 1.16mA, when the control current is 1.16mA, can ensure that the external force is far greater than the threshold, between the nozzle and the baffle plate in positioner is fully open, control valve is in full throttle state. At this point, the equivalent section area of the small hole is determined by the parameter $\text{Max}$. Adjust the maximum value of the equivalent section area of small hole in model, make measured valve position signal and simulation valve position signal match, then the $\text{Max}$ is the maximum value of the equivalent section area, $\text{Max} = 1.45e-6$, as shown in Fig.6 below.

![Figure 6. Parameter identification of parameters Max.](image)

Then, operate the step test of the preset valve position signal from 0-37, its corresponding control current signal from 0mA to 0.4292mA, when the control current is 0.4292mA, can ensure that the external force is far less than the threshold, there is no complete opening between the nozzle and the baffle, the control valve is not in full throttle state. At this point, the equivalent section area of the small hole is determined by $kF$. Adjust the ratio coefficient ($k$) of the equivalent section of the small hole and the external force in model, make measured valve position signal and simulation valve position signal match, then the $k$ is exact value, $k = 0.275e-11$. as shown in Fig.7 below.
Finally, because the $S_x$ is a continuous change (i.e., the $S_x$ is a continuous function), $\text{Threshold} = \frac{\text{Max}}{k}$, $\text{Threshold} = 5.31 \times 10^5$.

**Model Time Domain Verification**

**Verification Scheme Design**

First, operate step simulation experiment of different amplitude to simulation model, to valve position response, calculate time domain index of the final position value, rise time, accommodation time and ISE value; Secondly, operate step experiment of different amplitude to actual valve, to valve position response, calculate time domain index of the final position value, rise time, accommodation time and ISE value; Finally, compared the time domain performance index of the two groups is close to.

**Verification Result Analysis**

Because of the length of the space, only the open loop step test of 35-0-35 is shown (The sampling period 20ms, the duration of each step is 60s). Contrast the results, as shown in Fig. 8, Fig. 9. (1) There is a phase difference between the simulation valve and the actual valve; (2) Amplitude error; (3) Failed to simulate the distortion in the actual valve.
Figure 9. Detail diagram of valve position response between simulation valve and actual valve.

Through actual and simulation step experiment, analysis the experimental data, and calculate its dynamic performance index, as shown in Table 2:

| Signal type index | Measured signal | Simulation signal | Error percentage |
|-------------------|-----------------|-------------------|-----------------|
| final position value(%) | 15.6 | 15.6 | 0% |
| rise time /s | 6.18s | 5.72s | 7.4% |
| accommodation time /s | 9.52s | 8.48s | 10.9% |
| ISE value | 30899 | 33614 | 8.79% |

Among, the final position value is valve position when it is stable finally; rise time is the response from the final 10% to the final 90% of the time required; accommodation time is the valve position response arrival and maintain the final 5% of the shortest time required; ISE value is integral squared error between the measured valve position or simulation valve position and final position value, \( ISE = \int_{t_1}^{t_2} e^2 dt \), the integration time is set at fiftieth points to 3000th points. The experimental sampling frequency is 50 points per second.

Conclusions
In this paper, the modeling and parameter identification method of mass flow model and equivalent orifice area model are described in detail. Designing experiments and verifying the accuracy of the modeling and parameter identification method. There is a certain error in the valve position response to the actual valve, but the error is within the acceptable error range.

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