Experimental Research on a Kind of High-pressure Hot Gas Servo Valve Based on PWM Principle

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Abstract. High-pressure hot gas servo valve based on PWM principle is widely used in the solid attitude control system of kinetic kill vehicle and other aircrafts. In this paper, a kind of hot gas servo valve is proposed and its mathematic model is established. Also, the pressure in the chamber is tested and compared with simulation results to prove the model valid. In order to test the dynamic performance, an indirectly method of testing the piston's position is put forward and the delay time of the electromagnet and valve is tested. The results reveal that the hot gas servo valve designed in this paper has good dynamic performance and can satisfy the requirements of solid attitude control system.

1. Introduction

The hot gas servo valve based on PWM (pulse width modulation) principle works under the hot gas which is supported by the gas generator. It received PWM signal and regulates average thrust by controlling the ratio of two nozzles' switch time, which can control the gas flux. The thrust system is capable of producing continuously variable control thrust according to task comparing with the conventional thruster. This can realize aircraft's high-speed and accurate maneuverability[1-3], so they are widely used in solid divert and attitude control system (SDACS) and trajectory correction system of kinds of aircrafts, such as kinetic kill vehicle (KKV), trajectory correction rocket projectile, etc[4-6].

The dynamic performance of the hot gas servo valve is very import which decides the precision of the control system[7,8]. The import indicator of the dynamic performance is dynamic delay time, which is the time interval from sending out the control signal to producing thrust. The increase of the dynamic delay time will influence the dynamic performance of the control system and increase the miss distance, which results in reducing guidance accuracy.

In this paper, we propose a kind of hot gas servo valve based on PWM principle and establish its mathematic model. Then the pressure in the control chamber is tested and compared with the simulation result to verify the validity of the established model. Experimental research is done on its dynamic performance and an indirect method of testing the delay time by testing the piston's position is put forward. The experiment method and result are expected to provide reference for the structural design and experimental research of the hot gas servo valve.

2. Mathematic model

The hot gas servo valve designed in this paper is shown in Figure 1. The hot gas flows into the valve from the inlet and a small part goes into the control chamber through the fixed orifices f_1 and f_3 as

control media. The adjustable orifices f_2 and f_4 are enclosed by the electromagnet and the outlet of the control chamber. As shown in Figure 1, when the adjustable orifice f_2 is closed and f_4 is open, the pressure is increased in control chamber 1 and decreased in control chamber 2. Then the pressure difference is formed and increased gradually. When it's large enough, the piston is driven to move right. The rocker arm is pulled to revolve around its axis and block the Laval nozzle in the left side. Eventually, the hot gas flows out through the right Laval nozzle to produce thrust.

The orifice model of the valve is shown in Figure 2. The symbols p_0 and p_b are the gas supply pressure and atmospheric pressure separately. The orifice f_i (i =1,2,3,4) are the same with those shown in Figure 1. The symbol q_{mi} (i =1,2,3,4) means the mass flow of the four orifices and q_{ma}, q_{mb} are the mass flow of the control chamber 1, 2.
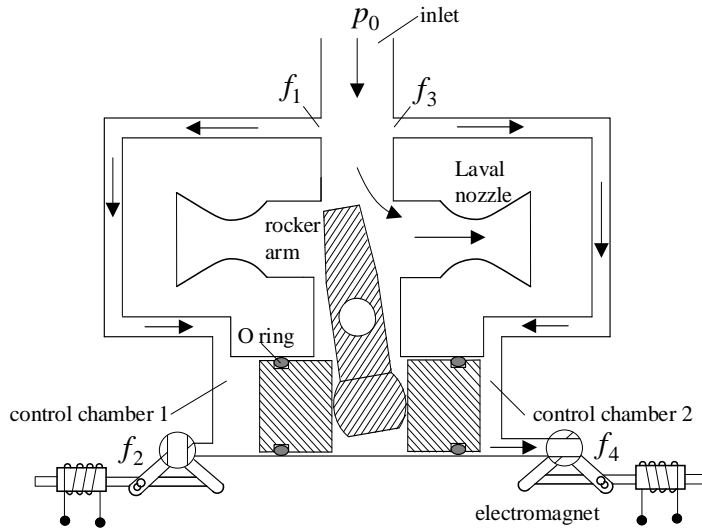

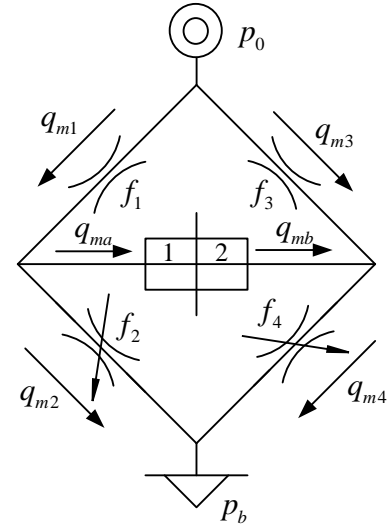**Figure 1.** Schematic of the hot gas servo valve

Figure 2. Orifice model diagram

In order to obtain the mathematic model of the valve, we assume that:
- The gas is perfect.
- The hypothesis of an adiabatic process is reasonable.
- The pressure and temperature within the control chambers are homogeneous.

Then the motion equation of the piston can be written as:

$$M\ddot{x} = A(p_1 - p_2) - F_L \tag{1}$$

Where M, x, A, p_1, p_2, F_L mean the mass, displacement, end-face area of the piston, the pressure of the two control chambers and the equivalent resistance of the piston respectively.

The pressure and temperature of the two control chambers are calculated by the following equations:

$$\begin{cases} \dot{p}_1 = \dfrac{k}{V_{01}+Ax}\left(q_1^+ R T_0 - p_1 \dot{x} A\right) \\[2ex] \dot{p}_2 = \dfrac{k}{V_{02}-Ax}\left(q_2^+ R T_0 - q_2^- R T_2 + p_2 \dot{x} A\right) \\[2ex] \dot{T}_1 = \dfrac{T_1 \dot{x} A}{V_{01}+Ax} + \dfrac{T_1 \dot{p}_1}{p_1} - \dfrac{R T_1^2 q_1^+}{p_1\left(V_{01}+Ax\right)} \\[2ex] \dot{T}_2 = \dfrac{T_2 \dot{x} A}{V_{02}-Ax} + \dfrac{T_2 \dot{p}_2}{p_2} - \dfrac{R T_2^2\left(q_2^+ - q_2^-\right)}{p_2\left(V_{02}-Ax\right)} \end{cases} \tag{2}$$

Where k, R, T mean the specific heat ratio, gas constant and the temperature of the working media. V_{01}, V_{02} are the initial volumes of the two control chambers respectively. q_1, q_2 mean the mass flow of the two control chambers. The subscript 0 means the parameters of the gas source and the superscript +, - represent the input and output, which are calculated by the equations as follows:

$$q_m = q_m\left(f,p,p_e,T\right) = \begin{cases} \dfrac{\mu f p B}{\sqrt{T}}\varphi\left(\dfrac{p_e}{p}\right) & \dfrac{p_e}{p} > C_{t1} \\[3mm] \dfrac{\mu f p C}{\sqrt{T}} & \dfrac{p_e}{p} \leq C_{t1} \end{cases} \tag{3}$$

Where μ, f mean the flow coefficient and the area of the orifice. B, C, C_{t1} and $\varphi(p_e/p)$ are coefficients related with the gas property and given as:

$$B = \sqrt{\frac{2k}{R(k-1)}}, C = \left(\frac{2}{1+k}\right)^{\frac{1}{k-1}}\sqrt{\frac{2k}{R(k+1)}}, \varphi\left(\frac{p_e}{p}\right) = \sqrt{\left(\frac{p_e}{p}\right)^{\frac{2}{k}} - \left(\frac{p_e}{p}\right)^{\frac{k+1}{k}}}, C_{t1} = \left(\frac{2}{1+k}\right)^{\frac{k}{k-1}} \tag{4}$$

Then the mass flow q_{mi} (i =1,2,3,4) can be calculated as:

$$q_{m1} = q_m\left(f_1, p_0, p_1, T_0\right); q_{m2} = q_m\left(f_2, p_1, p_b, T_0\right);$$
$$q_{m3} = q_m\left(f_3, p_0, p_2, T_1\right); q_{m4} = q_m\left(f_4, p_2, p_b, T_2\right). \tag{5}$$

3. Experiment research

3.1. Delay time of the electromagnet

The electromagnet receives the PWM control signal and overcome the load to drive the armature to plug the orifice f_2 or f_4. It's necessary to analyse the motion of armature as the delay time of the electromagnet is part of hot gas servo valve's delay time.

We connected a small resistor with the coil and test its voltage value to obtain the delay time of the electromagnet. The experimental results are shown in Figure 3 (without load) and Figure 4 (with load, the pressure is 7MPa).
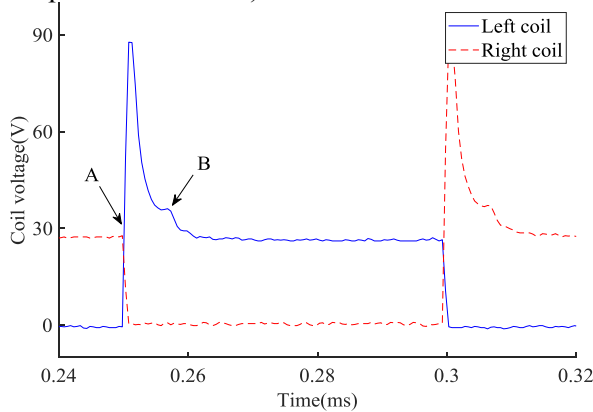

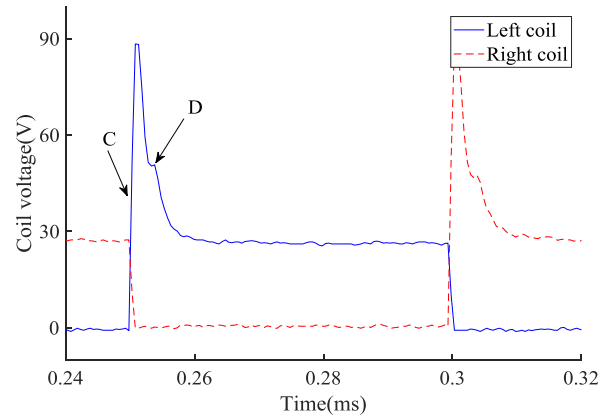**Figure 3.** The coil's voltage without load   **Figure 4.** The coil's voltage with load

It's observed that the delay time of the electromagnet without load is 7ms (e.g. t_{AB}) in Figure 3 and 3ms (e.g. t_{CD}) with load in Figure 4. The delay time with load is shorter than without load because the direction of the force generated by the gas flowing out from the orifice is the same with the armature's motion.

3.2. Delay time of the valve

In order to test the delay time of the valve, two pressure sensors were applied to test the pressure in the two control chambers. Also, we assembled magnetic sheets on both sides of the piston and Hall sensors on the body correspondingly. The output signals of the Hall sensors are compared to obtain the

piston's position signal which is contrast with the control signal to calculate the delay time indirectly. The principle of the test system is shown in Figure 5 and the experiment devices in Figure 6.
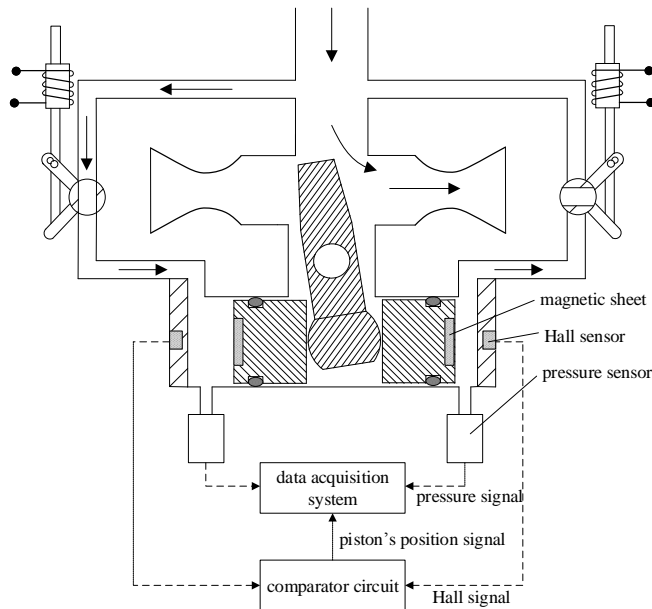

Figure 5. Schematic of the test system

Figure 6. Diagram of the experiment

3.2.1. Experiment of the pressure in the control chambers The pressure in the control chambers was tested and compared with the simulation result calculated by the model in section 2. When the control signal is send out at time 0, the experimental and simulation results in one cycle are shown in Figure 7.
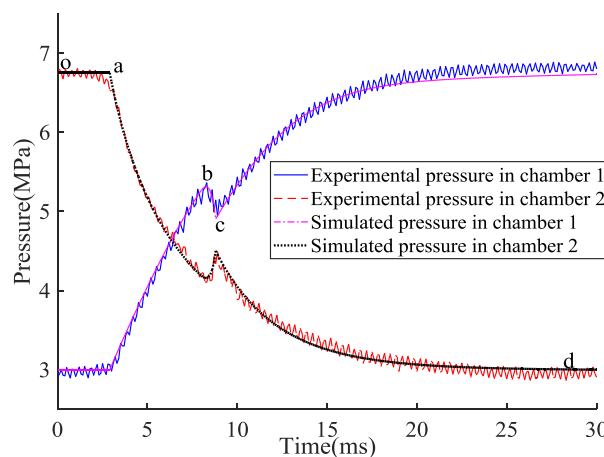

Figure 7. Simulation and experiment result of the pressure in the control chamber

In Figure 7, we can see that the experiment and simulation pressures are consistent, so the validity of the mathematic model in section 2 can be verified. Meanwhile, the time interval between the control signal and the pressure changing point (*a* in Figure 7.) is 0.3 millisecond, which is the electromagnet's delay time. This is consistent with the experimental result t_{CD} in Figure 4.

Then we divide the remaining working process into 3 parts. The first part is from point a to point b, which is called prepare phase. In this phase, the pressure in the two control are changing, but the pressure difference isn't large enough to drive the piston. The prepare phase's time t_{ab} is 5ms. The second part is from point b to point c, which is called motion phase. The piston moves to the other side under the pressure difference at this stage. The last part is from point c to point d, which is called stabilizing phase. The pressure becomes stable gradually until the next control signal comes.

3.2.2. Experiment of the piston's position The parts of testing the piston's position are shown in Figure 8. The Hall sensor is Honeywell's SS495A1 which is installed in the plug by high temperature glue and latching mechanism. SS495A1 is a kind of linear sensor and the relationship between its output voltage and its distance from the magnetic field is linear. But the magnetic field of the magnetic sheet is non-uniform, it's necessary to calibrate the sensor's output voltage and its distance from the magnetic sheet. The calibration result is shown in Figure 9. It can be seen that the output voltage has a linear relationship with the distance when it's between 2mm and 4mm. The piston's stroke is 1.6mm, so we set the distance in this range to realize the linear output.
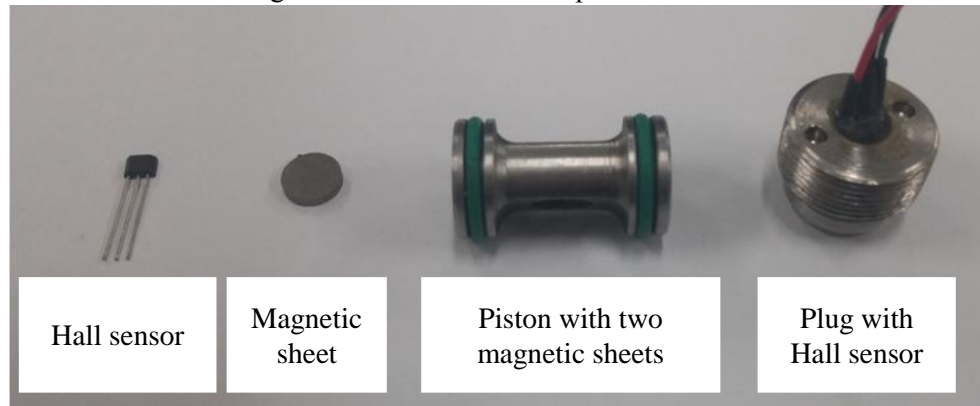

| Hall sensor | Magnetic sheet | Piston with two magnetic sheets | Plug with Hall sensor |

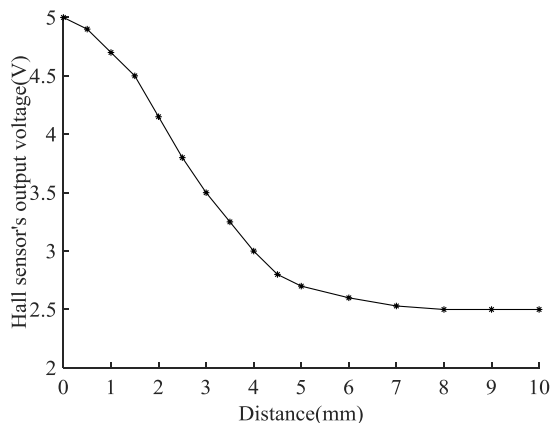**Figure 8.** Parts of the testing system

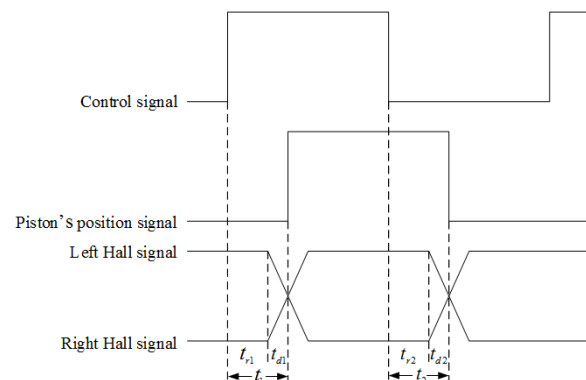**Figure 9.** Curve between the Hall sensor's output and the distance

Figure 10. The sequence diagram of control signal and Hall sensor signal

The test principle of comparing the control signal and the Hall sensor's signal is shown in Figure 10. The electromagnet receives the control signal and the pressure differential drives the piston's motion. When the piston goes through the middle position, the piston's position signal switches by comparing the two Hall sensors' signal. In Figure 10, t_1 and t_2 mean the delay time of the valve at the rising and falling edge. The symbol t_r is the delay time of the electromagnet and the prepare phase while t_d is the delay time of the piston's motion to the middle position. So the delay time can be expressed as follows by comparing Figure 10 and Figure 7:

$$t = t_r + t_d = t_{oa} + t_{ab} + (t_{bc}) \ , \quad t_r = t_{oa} + t_{ab} \tag{6}$$

Where (t_{bc}) means the time from point b to the piston's motion to the middle position, which is part of the time t_{bc}.

The experiment result is shown in Figure 11 and Figure 12. In Figure 11, we compare the control signal, the coil's voltage signal and the piston's position signal. It can be seen that the delay time of the hot gas servo valve is 8.5ms. In Figure 12, the piston's position signal and the pressure signal in

the control chamber are compared. It can be seen that the time of the piston's motion to the middle phase (t_{bc}) is 0.5ms.
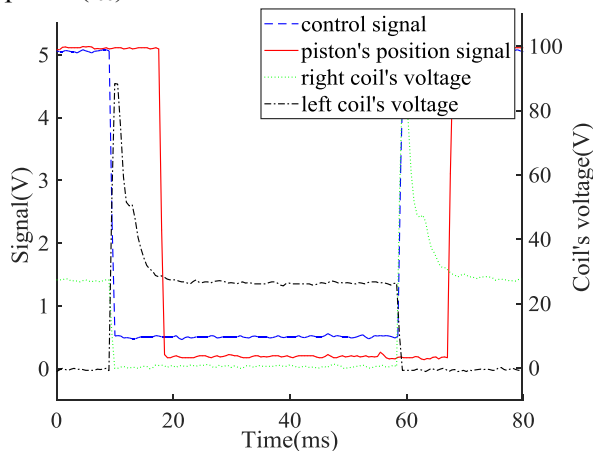

Figure 11. The diagram of control signal and piston's position signal
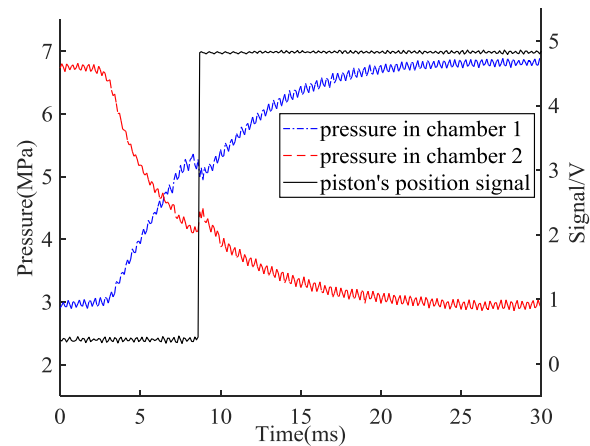

Figure 12. The diagram of pressure in control chambers and piston's position signal

4. Conclusion

The hot gas servo valve based on PWM principle can be used in solid attitude control system to produce attitude control thrust. A kind of hot gas servo valve is proposed in this paper and its mathematic model is established from the perspective of pneumatic theory. The pressure in the control chamber is tested and compared with simulation results to prove the model valid. In order to test the dynamic performance, the delay time of the electromagnet is tested and the piston's position is acquired by testing the Hall signal. So the delay time of the hot gas servo valve is tested to be 8.5ms. The results reveals that the gas servo valve designed in this paper has good performance and can be used in solid control attitude system.

References

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