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To cite this article: Zhong Yang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **470** 012013

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Performance Differences of a Solid Attitude Control Thruster under Different Working Media

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Abstract. The solid attitude control thruster is widely applied in solid attitude control system of kinetic kill vehicle and other aircrafts. Its static and dynamic performances have significant effect on the control performance and accuracy. The thruster works under hot gas generated from the gas generator, so compressed air must be used for its detection. In this paper, a kind of solid attitude control thruster was proposed and its working principle was analysed. Theoretical and experimental research was done on the static and dynamic performances of the thruster. The results will provide a reference for the detection of the solid attitude control thruster's static and dynamic performances.

1. Introduction

The solid attitude control thruster is widely applied in various kinds of aircrafts, such as kinetic kill vehicle (KKV) and trajectory correction rocket projectile, etc. It received PWM (pulse width modulation) signal of certain frequency and regulates thrust to control the attitude according to the deviation of actual and ideal trajectory [1-5]. The static and dynamic performance indicators are very important which have a great influence on the control ability [6]. One of the static performance indicators is the value of thrust when the nozzle is wide open. It's an important manifestation of the thruster's control ability. And one of the most important dynamic performance indicators is dynamic delay time which is the time interval from the sending time of control signal to the generating time of thrust. It has a great influence on the control accuracy and dynamic performance of the attitude control system [7,8].

The thruster works under the hot gas from gas generator, so it can't cyclically utilize. Therefore, compressed air will be used to detect the thrusters instead of hot gas. During production compressed air will be used to detect the thrusters firstly and then hot gas will be used for spot check. Therefore, it's important and necessary to study the static and dynamic performances between compressed air and hot gas. In this paper, we proposed a kind of solid attitude control thruster and analysed its working principle. Then we did theoretical and experimental research on the static and dynamic performances of the thruster. The result will provide a reference for the detection of the solid attitude control thruster's performances.

2. Structure model

The solid attitude control thruster designed in this paper is shown in Figure 1. The hot gas flows into the thruster 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 thruster is shown in Figure 2 [9]. The symbols P_s and P_b are the gas source pressure and backpressure separately. The orifices 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.

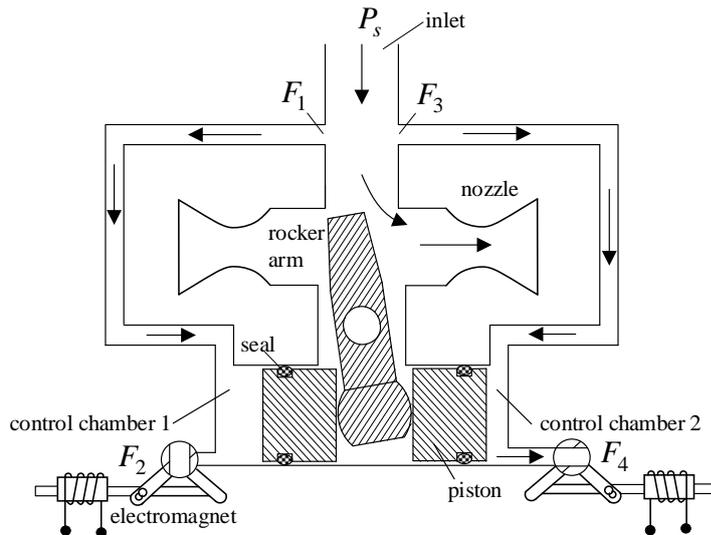


Figure 1. Schematic of the solid attitude control thruster

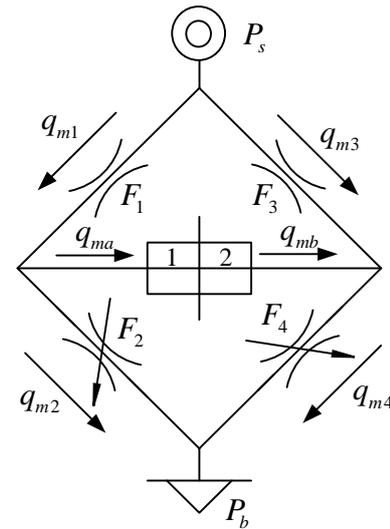


Figure 2. Orifice model diagram

The solid attitude control thruster works under hot gas as its working media which is destructive. Thus, compressed air must be used instead of hot gas to detect the thruster. Except temperature, compressed air and hot gas are also different in some aspects as follows:

- The specific heat ratio of the hot gas is lower than the compressed air. It's related to the gas component that the compressed air is composed of diatomic gas while the hot gas is polyatomic gas.
- The energy of the hot gas is much larger than the compressed air. It's because the temperature T and the gas constant R of the hot gas are larger than the compressed air.

The main parameters of the compressed air and hot gas in the experiment are listed in Table 1.

Table 1. The main parameters of the compressed air and hot gas

Designation	Specific heat ratio k	Gas constant R (J/kg·K)	Temperature T (K)	Pressure P (MPa)
Compressed air	1.4	287	300	7
Hot gas	1.25	360	1100	7

3. Research on static thrust

The static thrust is a significant indicator to evaluate the control ability of the attitude control thruster and also the primary indicator of design process. Therefore, it's important to study the static thrust. The difference between the static thrust of the two working media will decide whether the thruster can be tested by compressed air.

We assume that the thruster works under the optimum expansion condition, then the thrust can be calculated by the following equation:

$$F = \dot{m}V_e = \Gamma F_V P A_t \tag{1}$$

In equation (1), F means the nozzle's thrust and m , V_e are the mass flow rate and the velocity of exhaust, which can be given as:

$$\dot{m} = \Gamma P A_t / \sqrt{RT_0} \tag{2}$$

$$V_e = \sqrt{RT_0} \cdot F_V \tag{3}$$

In equation (2) and (3), P and T_0 mean the pressure and temperature of the gas in the inlet of the nozzle and R is the gas constant. Γ is a gas parameter and given as:

$$\Gamma = \sqrt{k} \left(\frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}} \tag{4}$$

F_V is the function of the flow velocity which can be calculated as follows:

$$F_V = \sqrt{\frac{2k}{k-1} \left[1 - \left(\frac{P_b}{P} \right)^{\frac{k-1}{k}} \right]} \tag{5}$$

P_b is the backpressure of the nozzle's outlet and k is the specific heat ratio of the gas.

It can be seen that the static thrust is decided by the property of the gas when the pressure is definite. Then the static thrusts under compressed air and hot gas are compared as follows:

$$\frac{F^*}{F} = \frac{\Gamma^* F_V^*}{\Gamma F_V} = 1.03 \tag{6}$$

In formula (6), the superscript * means the parameters of hot gas. The static thrusts under compressed air and hot gas are consistent. Therefore, it's feasible to detect the static thrust by compressed air instead of hot gas in theory.

Then we do experiment on static thrust of the thruster. We fixed the piston to one side in order to generate thrust on one side. Then the thrust is tested by the force sensor and the experiment under hot gas is shown in Figure 3. The experimental results under compressed air and hot gas are shown in Figure 4. It's observed that the experimental result corresponded with the theoretical result. Therefore, the static thrust can be detected by compressed air.



Figure 3. Experiment of the static thrust under hot gas

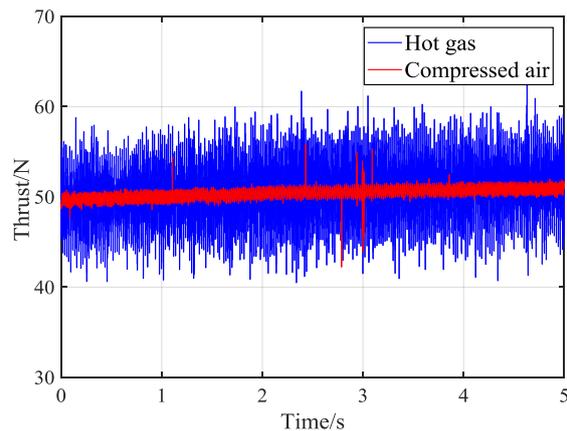


Figure 4. Static thrust of compressed air and hot gas

4. Research on dynamic delay time

The dynamic performance of the thruster is mainly characterized by dynamic delay time, which is the time interval from sending the control signal to the switching of the thrust. In order to test the delay time, 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 two Hall sensors were compared by the comparator circuit to obtain the piston's position signal. When the piston goes through the middle position, the piston's position signal goes to the opposite electric level. Therefore, the dynamic delay time can be obtained by contrasting the control signal with the control signal indirectly. The principle of the test system is shown in Figure 5 and the experiment devices in Figure 6.

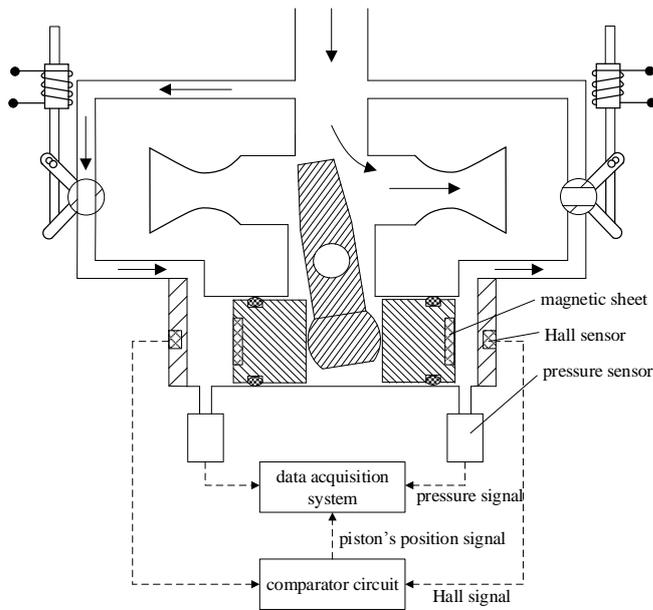


Figure 5. Schematic of the test system



Figure 6. Diagram of the experiment

The thruster was tested under compressed air and hot gas separately and the pressure of gas source was 7 MPa. The pressure curves in the two control chambers under compressed air and hot gas are shown in Figure 7 and the piston's position signal contrasted with the control signal under the two media are shown in Figure 8.

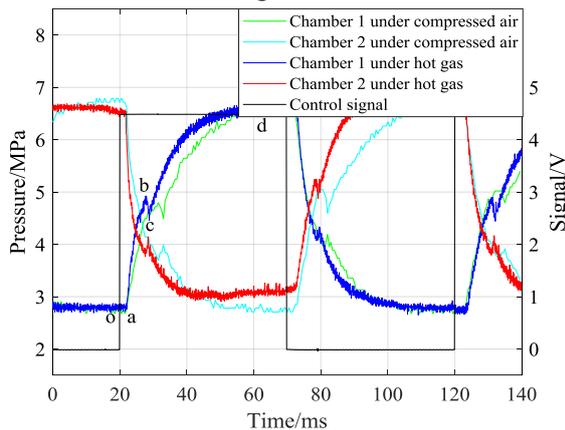


Figure 7. Pressure signal in the two control chambers under compressed air and hot gas

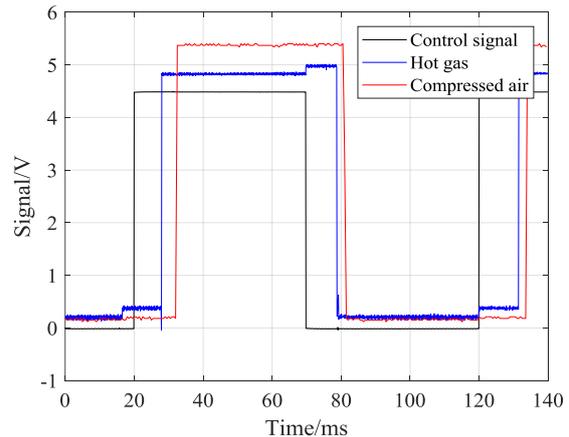


Figure 8. Piston's signal and control signal under compressed air and hot gas

Using pressure in chamber 1 under hot gas as an example, the working process can be divided into 4 parts obviously as shown in Figure 7. The first part is from point o to point a which is the delay time of the electromagnet. The second 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 third 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. In Figure 8, the dynamic delay time of the thruster can be obtained by contrasting the control signal and the piston's position signal. The delay time of every stage can be obtained from Figure 7 and 8 and the results are shown in Table 2.

Table 2. The delay time of every stage (unit: millisecond)

Media	Delay time of the electromagnet	Prepare stage	Motion stage	Whole delay time
Compressed air	3.0	6.8	1.1	10.4
Hot gas	3.0	4.6	0.9	8.0

The pressure of hot gas varies more rapidly than compressed air during working process, especially in the prepare phase and stabilizing phase and the dynamic delay time of hot gas is obviously less than compressed air. Considering that the proportion of the prepare phase is the highest among all the phases, the difference between the dynamic delay time under compressed air and hot gas is concentrated in the prepare phase.

In the prepare phase, the pressure in the control chamber 1 is calculated as follows:

$$\dot{P}_1 = \frac{k}{V_1} Q_1 R T_s \quad (7)$$

In equation (7), P_1 and V_1 mean the pressure and volume of the control chamber 1 and Q_1 means the mass flow of the working media flowing into the control chamber 1. T_s is the temperature of source gas. The stream of the orifice F_1 is subcritical flow and the flow equation is given below:

$$Q_1 = \frac{\mu F_1 P_s}{\sqrt{T_s}} \varphi \left(\frac{P_1}{P_s} \right) \quad (8)$$

where

$$\varphi \left(\frac{P_1}{P_s} \right) = B \sqrt{\left(\frac{P_1}{P_s} \right)^{2/k} - \left(\frac{P_1}{P_s} \right)^{(k+1)/k}} \quad (9)$$

Where B is a parameter related to the gas and calculated as follows:

$$B = \sqrt{2k/R(k-1)} \quad (10)$$

The time of the prepare phase is obtained by integration:

$$t = \frac{V_1}{(k-1)\mu F_1 R B \sqrt{T_s}} \phi(k) \quad (11)$$

where

$$\phi(k) = \sqrt{1 - \left(\frac{P_b}{P_s} \right)^{k-1}} - \sqrt{1 - \left(\frac{P_1}{P_s} \right)^{k-1}} \quad (12)$$

The proportion of the delay time of prepare phase under compressed air and hot gas according to the equation (12) is calculated as 1.53 while the experimental result is 1.48 according to the data in Table 2. The experimental and calculation results are consistent basically. The delay time of the prepare phase under compressed air is about 50% more than hot gas while the delay time of motion phase under the two media has little effect on the dynamic delay time. Therefore, we can establish the evaluation system by the equation. When detecting the thruster, we should firstly estimate the performance of the thruster under hot gas by the experiment result of compressed air. Then carry out

spot check on thrusters by hot gas in order to correct the evaluation system. Consequently, the detection of the thrusters can be realized by compressed air.

5. Conclusion

The solid attitude control thruster works under hot gas which is destructive. Therefore, it must be detected by compressed air. In this paper we proposed a kind of solid attitude thruster and analysed its working principle. Then we did theoretic and experimental research on the static thrust and dynamic delay time of the thruster under compressed air and hot gas. The two kinds of media had little effect on static thrust while a significant impact on dynamic delay time. The evaluation system of detecting the thruster was established preliminary. The result will provide feasible basis for the detection of the solid attitude control thrusters.

Acknowledgments

This work was supported by the Training Fund of Shandong Natural Science Foundation (Grant NO. ZR2017PEE016) and the Talent Introduction Project of Ludong University (Grant NO. LB2016002).

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