Magnetic Structure Design for Frictionless Proportional Solenoid Valve Based on Large Leaky Magnetic Circuit

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Abstract. In the spacecraft micro propulsion system, the proportional solenoid valve of milligram flow is a very important component, which is used to achieve the system pressure and flow proportional adjustment. It is required to reach the high precision and high resolution control of thruster thrust. This paper investigated a new design based on leaky magnetic circuit and frictionless structure of armature suspension. The use of magnetic materials in the lower zone B with small slope and good linearity characteristic reduces the sensitivity of the electromagnetic force changing with displacement. Meanwhile, the support with flat spring is used to keep the valve armature suspended, and avoids the interference of friction force and inner pollution of abrasive dust. Thus the frictionless movement of the proportional valve can be realized with improved proportional accuracy and linearity. The results of simulation and experimental verification show that this structure design is feasible with excellent performance, which can significantly improve the precision adjustment ability of electric propulsion system.

Keywords: Micro propulsion system · Proportional solenoid valve · Electromagnetic simulation · Large leaky magnetic circuit

1 Introduction

Solenoid proportional valve has a very important application value. Especially with the development of spacecraft electric propulsion technology in the spacecraft propulsion system pressure, flow proportional regulation. The need for high precision and high resolution electromagnetic proportional valve for mg/s level flow rate for accurate regulation. For example, MOOG developed a solenoid proportional valve for the deep space exploration satellite DS-1 xenon proportional flow supply system to accurate regulate the pressure, flow rate [1–3]. In recent years, some microsatellite propulsion system, gravitational wave and gravity field detection scientific research mission traction of a

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new generation of storage and supply system also put forward an urgent demand for higher precision and high reliability proportional solenoid valve technology [4–10].

Solenoid proportional valve is a key component of electric-gas conversion, with the advantages of small weight, easy control, high reliability and long life, especially suitable for gas flow control. The solenoid valve needs to be adjusted for position adjustment by balancing the combined force of electromagnetic force and spring force with hydraulic pressure. Schaeffler KG of Germany developed a high pressure resistant one-way stepped annular proportional solenoid valve and studied the displacement-force characteristics; Li Yong of Zhejiang University and others analyzed the stroke gap and isolation angle affecting the characteristics of the solenoid proportional valve [11–14]; Wang Xiaogang et al. of the Shanghai Institute of Space Propulsion conducted simulations and ground experiments on various factors affecting the dynamic characteristics of solenoid valves in the context of liquid rocket engines for space applications. These conventional proportional solenoid valves successfully achieve electric-displacement proportional control with a structure mostly based on frictional motion sub-structure [15]. With the development of aerospace technology, there is a need for its fluid control component products to be frictionless and avoid excess contamination, thus achieving higher reliability.

This paper introduces a frictionless solenoid proportional valve based on the principle of large magnetic leakage with the application in a spacecraft propulsion system flow supply system as the research objective. The proportional solenoid valve takes advantage of the small slope of the magnetic material B-H curve at much lower B region, i.e., lower growth rate, and proposes a new magnetic circuit model to realize the frictionless design of the proportional solenoid valve. In this paper, simulation and experimental study of the magnetic circuit are conducted to verify the correctness of the model.

2 Mathematical Model

The large magnetic leakage solenoid proportional valve follows Kirchhoff's law of magnetic pressure and Maxwell's equations in the magnetic circuit and D'Alembert's equations of motion in the motion.

2.1 Mathematical Model of Magnetic Circuit

According to Kirchhoff's law of magnetic pressure, the magnetic circuit is calculated as follows:

$$IW = F_\delta + F_H + F_c \tag{1}$$

where I is the coil current, A; W is the number of the coil; F_δ is the working stroke gap magnetic potential loss; F_H is the non-working stroke gap magnetic potential loss; F_c is the magnetic potential loss of the magnetic conductor.

And:

$$F_\delta = B_\delta \frac{\delta}{\mu_0} \tag{2}$$

$$F_H = B_{\delta'} \frac{\delta'}{\mu_0} \tag{3}$$

$$F_c = H \times L \tag{4}$$

where B_δ is the working stroke gap magnetic flux density, T; $B_{\delta'}$ is the non-working stroke gap flux density; H is the magnetic potential corresponding to the magnetic flux density in the magnetic conductor, Ampere-turn/m; δ is working stroke gap, m; L is the length of the magnetic circuit, m; δ' is the non-working stroke gap, m; μ_0 is the air magnetic permeability, here is 1.257×10^{-6} H/m.

According to Maxwell's formula for electromagnetic suction, the force of attraction for the spool assembly is:

$$F_x = \frac{B_\delta^2 \times A}{2 \times \mu_0} \tag{5}$$

where F_x is the solenoid suction, N; B_δ is the working stroke gap magnetic flux density, T; A is the armature area, m^2; μ_0 is the air magnetic permeability, here is 1.257×10^{-6} H/m.

2.2 Solenoid Proportional Valve Spool Dynamic Mathematical Model

The mathematical model of the motion of the solenoid valve spool is shown in Eq. (6) to Eq. (8). Among them, Eq. (6) is the equation of motion of the spool of the solenoid valve opening process, Eq. (7) is the equation of motion of the moving parts of the solenoid valve closing process.

$$m_1 \frac{d\nu_{1a}}{dt} = F_x - F_{p1} - F_{f1} - F_{s1} \tag{6}$$

$$m_1 \frac{d\nu_{1b}}{dt} = -F_{p1} - F_{f1} + F_{s1} \tag{7}$$

$$\nu_1 = \frac{dx_1}{dt} \tag{8}$$

where m_1 is the mass of the spool and armature assembly, kg; ν_{1a}, ν_{1b} are the opening velocity and closing velocity of armature assembly, respectively, m/s; F_{p1} is the fluid pressure imbalance force, N; F_{f1} is the armature spring force, N; F_{s1} is the damping force, which is always opposite to the direction of motion, N; x_1 is the spool stroke, m.

3 Principle and Structural Design

3.1 Traditional Proportional Solenoid Valves and the Challenges they Face

As can be seen from the magnetic circuit model, the electromagnetic force is sensitive to displacement and can easily change dramatically with the armature movement thus destroying the force balance. Therefore, the ideal proportional solenoid valve is to make the electromagnetic force is not sensitive to displacement, but only proportional to the driving voltage or current, so that it is balanced with the spring force acting on the spool. Therefore, the proportional solenoid valve magnetic circuit is different from the ordinary switching solenoid valve, whose electromagnetic force generally consists of two parts, one of which increases with the increase of displacement, while the other decreases with the decrease of displacement, so that the combined force changes less with displacement at the same driving current or voltage, and is only related to displacement.

The structure of the conventional proportional solenoid valve is shown in Fig. 1. The working principle is: when the proportional solenoid valve control coil is given a certain current, two magnetic circuits will be formed, one magnetic circuit (MC) Φ_1 from the end cap through the bottom of the basin-shaped pole boot along the axial working stroke gap into the armature, through the outer conductor back to the end cap, resulting in axial force F_{ml}. The other magnetic circuit Φ_2 through the basin-shaped pole boot conical periphery (the front part of the guide sleeve) radially through the working stroke gap, and then into the armature, and then converge with Φ_1, forming an additional axial F_{m2}. The two are combined to obtain the horizontal force characteristics of the proportional solenoid output force Fm relative to the armature displacement, thus realizing the electric-machine characteristic relationship shown in Fig. 2.

Although the traditional proportional solenoid valves have different structures, they all use the bypass splitting method to reduce the electromagnetic force increase, the disadvantages of this structure mainly include: (1) consistency. The performance of the solenoid valve requires high requirements for the shape of the pole shoe. There are high requirements for machining accuracy, and it is not easy to maintain consistency in production; (2) friction structure. Because the spool needs to leak through the wall during the movement, the spool and the wall spacing is small, even if the spool is suspended by the leaf spring, but there is still a risk of friction, easy to be affected by the environment to produce friction, thus affecting the product proportional performance.

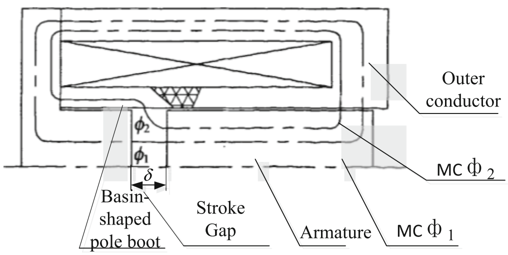

Fig. 1. Proportional solenoid valve magnetic circuit structure schematic diagram

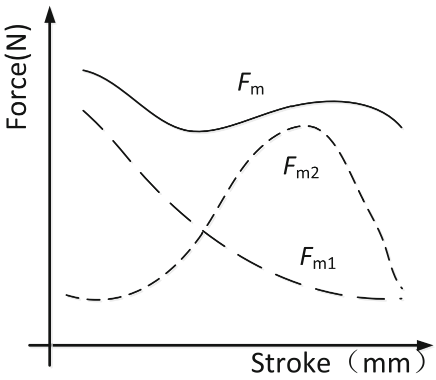

Fig. 2. Proportional solenoid valve displacement-force characteristics

3.2 Basic Principle of Large Magnetic Leakage Proportional Valve

As stated, the essence of a proportional valve is to reduce the sensitivity of the electromagnetic force to changes in displacement so that it is only proportional to the drive voltage or current, thus balancing the electromagnetic force with the spring force acting on the spool.

Figure 3 is a typical structure schematic diagram of a beat-close switching solenoid valve (frictionless structure solenoid valve), and Fig. 4 shows the growth of electromagnetic force with spool displacement under pulse drive (50 ms on/50 ms off), from which it can be seen that the growth of electromagnetic force can be divided into four stages, A, B, C and D. The electromagnetic force changes faster in stages B and C, and slower in stages A and D. The initial position of the armature is shown in Fig. 4, when the armature starts to move, the electromagnetic force increases slowly in the initial stage, while after a period of movement, the electromagnetic force increases rapidly, which makes the valve open completely to reach the final position. Similarly, when the solenoid valve is powered off, the electromagnetic force decreases rapidly.

As can be seen, the increase in electromagnetic force and armature displacement is very large, when the armature closer to the armature, the electromagnetic force increases much faster than the linear increase in spring force; and in the closing phase, the armature away from the valve body, the electromagnetic force changes extremely fast. This is also the reason why the proportional control cannot be achieved with the common clap type solenoid valve. However, by observing Fig. 4, it is noted that the electromagnetic force changes more slowly in the two areas of A and D. It is possible to balance the spring force in these two stages to obtain the proportional driving characteristics.

Analysis of Eq. (5) shows that if the increase rate with displacement is slow, as in Fig. 8, part A and D curves, it is possible to make the electromagnetic force in this region insensitive to displacement, but only proportional to the driving voltage or current, so that it is balanced with the spring force acting on the spool, and the corresponding displacement can be obtained by controlling the voltage or current. Therefore, a magnetic circuit design is needed to make the valve work in the low B region throughout the displacement interval.

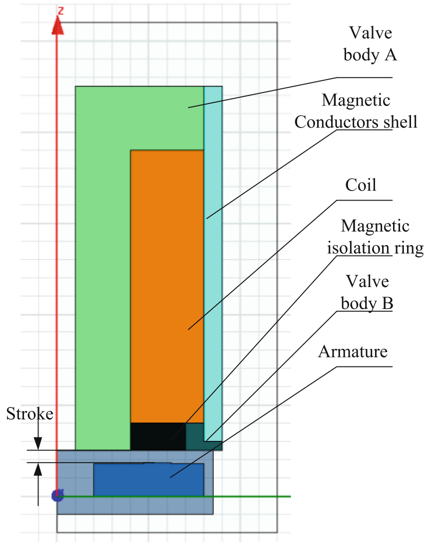

Fig. 3. Frictionfree switching type solenoid valve

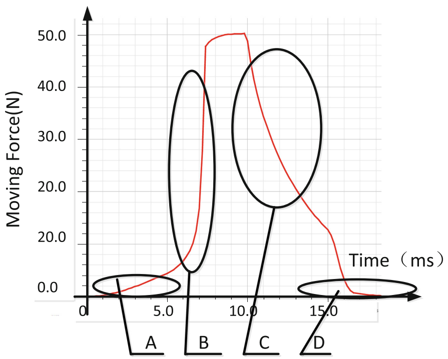

Fig. 4. Electromagnetic force-spool motion displacement curve

3.3 Large Magnetic Leakage Proportional Valve Composition

The frictionless proportional solenoid valve designed according to this principle is shown in Fig. 5. The figure makes the proportional solenoid valve work always work in the low flux area by setting the a and b values, i.e., the force balance of the armature is achieved through the large leakage magnetic circuit, so it is a proportional valve based on the large leakage magnetic circuit. Since both a and b gaps are large, the proportional solenoid valve of this structure does not rub against the wall, which improves the reliability of the product's operation.

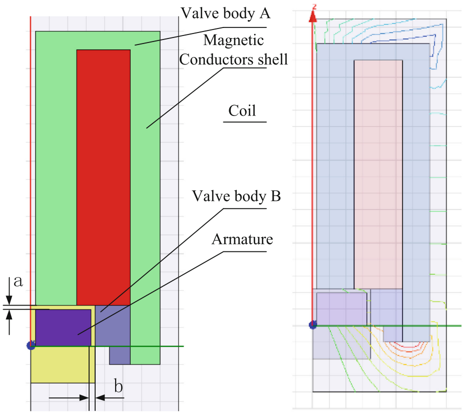

Fig. 5. Friction-free proportional solenoid valve diagram

Table 1. Main requirements for proportional valves

Parameter items	Value
Voltage (VDC)	0–15
Orifice diameter (mm)	0.5
Pressure (MPa)	0–2
Power consumption (W)	<8
Reference item	0–15

4 Design and Simulation

4.1 The Process of Design

Since the proportional solenoid valve is in the lower B phase during the whole working interval, the calculation method and thought process is completely different from the traditional switching solenoid valve. The calculation of this valve should start from the maximum position state of opening, and get the magnetic flux density B at this time → after that invert the required armature diameter → calculate the required number of ampere-turns → calculate the outer conductor magnet inside and outside diameter and other various parameters → calculate the enameled wire diameter → calculate the required spring stiffness.

4.2 Calculation and Simulation

The new frictionless proportional solenoid valve design is carried out for the following input conditions with the parameters shown in Table 1.

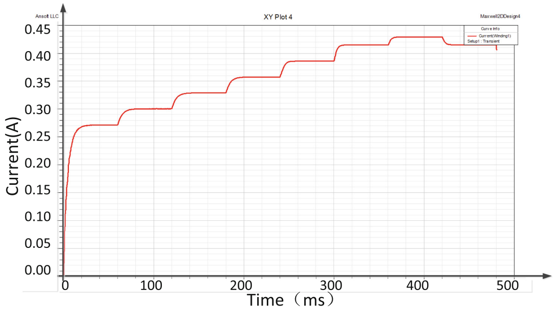

Fig. 6. Step voltage supply

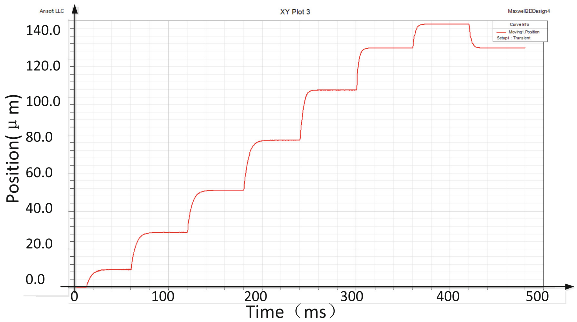

Fig. 7. Voltage-displacement curve

The following parameters were obtained:
Pressure: 0–2 MPa
Medium: N2, He
Stroke: 0–0.14 (>0.5/4) mm
Armature diameter: 10 mm
Turns of the ciol: 322 IW
Resistance Value: 36.5 ± 2 Ω
Spring stiffness: 50 N/mm
Power consumption: <7 w

Simulation of the electromagnetic characteristics was performed with Ansoft Maxwell software. First, a stepped driving voltage is loaded to the proportional solenoid valve, as shown in Fig. 6. Its corresponding armature displacement is shown in Fig. 7. From the simulation results, it can be seen that the valve successfully achieves the proportional voltage-displacement drive, and the action following and linearity of the armature are good.

The actual product developed with this design structure is shown in Fig. 8, and the test results are shown in Table 2. From the test results, the valve can achieve force balance and good stability in the working range of 0–15 V, and the maximum stroke reaches 0.152 mm. Although there is a certain hysteresis phenomenon between the lift

(a) Physical drawing of proportional valve

(b) Displacement test device

Fig. 8. Image of proportional solenoid valve

Table 2. Experimental data

Rise Stroke		Return Stroke	
Voltage (V)	Stroke (mm)	Voltage (V)	Stroke (mm)
0	0	15	0.152
10	0.035	14	0.142
11	0.05	13	0.125
12	0.08	12	0.092
13	0.105	11	0.07
14	0.135	10	0.04
15	0.152	0	0

and return, it can meet the needs of engineering applications for the closed-loop control electric propulsion system.

5 Conclusion

In this paper, a new frictionless proportional magnetic circuit is proposed, and a numerical simulation method is used to design, simulate and experimentally study the proportional solenoid valve used on a drag-free satellite, with the following conclusions.

(1) Proposed a novel design method and flow of proportional magnetic circuit by observing the force-displacement change curve of the switching solenoid valve.
(2) A frictionless proportional solenoid valve based on large magnetic leakage is designed for the control demand of proportional flow of a spacecraft, and through simulation and experiment, it is demonstrated that the design can achieve good proportional characteristics within 0–0.15 mm.
(3) This miniature solenoid proportional valve takes advantage of the small slope of the B-H curve of the magnetic material in the low B region, i.e., the low growth rate of the electromagnetic force, and designs a new magnetic circuit. The design of the magnetic circuit makes the solenoid proportional valve have proportional characteristics while the spool has a large clearance with the valve body, while using the flexible leaf spring technology to suspend the proportional valve, thus avoiding the shortcomings of the traditional solenoid proportional valve which is prone to friction.
(4) The magnetic circuit structure is different from the traditional structure, which not only realizes the frictionless motion of the valve, improves the proportional accuracy and reliability of the valve, but also reduces the dependence of the proportional valve on the machining accuracy of the boot part, making the consistency of the proportional valve better. Proportional valves based on this principle can be applied in a variety of working scenarios with fluid proportional control needs, and have a wide range of applications in the field of satellite propulsion system fluid control.

Authors' Contributions. For research articles with several authors, the following statements should be used "Conceptualization, WANG Xu-dong; methodology, Tan Shuiming; software, Zhang Zhen.; validation, Gao Chen-guang; project administration, Zhang Liang, and Wang Huanchun." All authors have read and agreed to the published version of the manuscript.

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