Design for improving the linearised flow control performance of large flow and high-pressure proportional valve

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Abstract: To improve the linearisation of the variable flow-regulate system under the open-loop control, a proportional solenoid valve with high-linearity performance was developed to meet that requirement of the high-precision and open-loop control. The design of the proportional solenoid valve evolves the optimisation of a magnetic circuit structure, the construction of a balanced pressure structure and the compensation of a feedforward control device. As for the solenoid, it is very challenging to meet the requirement of 95% linearity. A feedforward control device with the Bouc–Wen model and a quadratic inverse function model is a good solution to address the hysteresis problem and achieve better performance. The optimisation of a simple magnetic circuit with low sensitivity to the moving armature and a balance chamber for removing the pressure difference are both preconditions to make the compensation. The feedforward control device is the next step to eliminate the hysteresis problem and non-linear characteristics of the solenoid by solving model coefficients measured in the test. After the improvement in these aspects, the proportional solenoid valve can meet the demand of digital proportional flow control with >98% linearity and excellent repeatability, through the validation of both no-load and high-load performance tests.

1 Introduction

In recent years, the variable flow-regulate system with high linearity has become a hot point in the aerospace industry because of its flexible characteristic and easy to handle ability. Especially like applications in the soft-landing system of a lunar lander, the drag-free control system of an ultra-static satellite and the xenon storage system for electric propulsion [1–3].

The difference of aerospace proportional valves from some proportional valves commonly used in industrial applications is to pursue the high-linearity performance and the high reliability at the same time, without any possibility of repairing in the orbit. That means there is a limit to use the electro-hydraulic servo valve or the proportional motor valve in the propellant system of spacecraft under the condition of large amplitude vibration in the launching process. Thus, the solenoid valve and the piezoelectric valve have been regarded as feasible options for the spacecraft. Among them, the piezoelectric valve is more suitable to the micro or small flow systems because of its small displacement of the actuator with high frequency and high-speed response. In contrast, the proportional solenoid is a better way to adjust the valve's opening position with the variable input current for the higher flow regulation. It has many advantages, such as simple structure, easy assembly, secure processing, high reliability and low cost [4].

However, the hysteresis phenomenon of the solenoid valve is also needed to consider, especially under the high-load condition. (i) The high-pressure load with large flow rate causes the high criterion of electromagnetic force to activate the valve, leading to significant delays and a dead zone. (ii) Opening of solenoid seats can throw the valve into an unbalanced situation due to the sudden change in pressure, so the armature cannot keep stable at its throttling position under the perturbation. (iii) The non-linearity and hysteresis of electromagnetic material significantly affect the linearisation of the proportional solenoid valve, making a great difficulty in realising the open-loop control of the system [5, 6]. Therefore, the feedforward control device with the Bouc–Wen model was developed to meet the demand of the open-loop control with high precision. The Bouc–Wen model has been widely used for the compensation of hysteretic systems very well. It has been extensively adopted in many fields, such as magnetorheological dampers [7, 8], structural elements [9, 10], base isolation devices [11, 12] and piezoelectric ceramic actuators [13, 14]. However, very few researchers have employed the hysteresis compensation for the proportional solenoid valve using the Bouc–Wen model, because the solenoid hysteresis is too severe to narrow this gap. Thus, the optimised magnetic circuit and pressure-balance structure are needed to design in detail to keep the balance between the electromagnetic force and the load force. It is a very important precondition for control compensation. On this basis, the improved Bouc–Wen model with an inverse function is used to develop the proportional solenoid valve with a good linearity performance under the high-load condition.

2 Solenoid structure

The components of the total force acting on armature include electromagnetic force, pressure force and spring force used for sealing and return. The proportional flow adjustment requires that the armature can stop at any position in its movement from the zero-flow position to the maximum opening position with the balance among these three forces. So, the big challenge is that neither the electromagnetic force nor pressure force is the linear force over the stroke. That means the compensation of feedforward control device with the Bouc–Wen model hardly works under this condition unless this non-linear problem of these three combined forces is weakened first [15, 16].
2.1 Magnetic circuit design

As shown in Fig. 1, except the working gap called A-area gap as the stroke in the solenoid, the other non-working gap called B-area gap is also constructed in the magnetic circuit. Due to the existence of this B-area gap, the magnetic resistance of the magnetic circuit is enhanced, which can ensure that the valve's operating point is located within the low flux area as shown in Fig. 2. In this area, the electromagnetic curve can be regarded as approximately linear.

In this structure, the proportional pole shoe is another key to adjust the performance of the solenoid except for the B-area gap. In Fig. 3, it is easy to figure out the difference between the closed position and the open position. When the valve is closed, the magnetic resistance is relatively smaller due to the pole shoe. It is conducive to build up a bigger electromagnetic force to open the valve at the start point. When the valve is opening, the increment of an attractive force can be somewhat reduced under the influence of lengthening the distance δ from the pole shoe in the process of movement. That means the over speed of electromagnetic force increment going with the displacement is suppressed to match the spring force.

Meanwhile, the sharp angle α of the proportional pole shoe is also needed to design in detail to aim the change of electromagnetic force as linear as possible. In terms of pressure force, it should be neglected by constructing the pressure balance structure. Only in this way, it can be possible to keep the armature suspended at any position without being quickly attracted by the energised coil.

2.2 Pressure balance structure

As mentioned before, the differential pressure force must be eliminated for its negative effect on the large dead zones and a step change which leads to the unbalanced situation. As shown in Fig. 4, an upstream pressure chamber connects a downstream pressure chamber with the same flow area. These two chambers consisted of the valve stem, the valve body and valve seat that can remove the pressure difference between upstream and downstream.

When the valve is closed, the static pressure \( P_1 \) has the same flow area as \( P_2 \), so the differential pressure on the valve stem is zero to make a balance. At that time, both \( P_2 \) and \( P_3 \) are zero. Therefore, no matter how much the inlet pressure is, it cannot affect the threshold value of valve opening. Once the

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**Fig. 1** Proportional solenoid valve's magnetic circuit structure

1: Proportional pole-shoe; 2: Armature; 3: Shell; 4: Coil; 5: Iron core; 6: Spring; 7: A-area gap; 8: B-area gap

**Fig. 2** \( \Phi-I \) curve of the typical magnetic material

**Fig. 3** Comparison of magnetic characteristics at different positions

(a) The valve in a closed position, (b) The valve in an open position

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electromagnetic force is greater than the spring preloaded, the armature starts to move upwards. In that way, the valve is always working in the ‘approximate no-load’ state without the significant dead zone.

We assume that the armature stays at a particular middle position, and there should be a pressure drop between \( P_2 \) and \( P_2' \) due to valve orifice throttling when the valve is opening. At this point, \( P_2 \) equals to \( P_1 \) and \( P_2' \) equals to \( P_3 \), so the total lifting force on the valve stem \( P_1 + P_2' \) is the same to the combined downforce \( P_2 + P_3 \). In this case, the differential pressure can be approximately eliminated, leaving the valve in a pressure balance at any point in the moving process of the armature.

### 2.3 Simulation analysis

The simulation of the static characteristics of the proportional solenoid valve should be conducted using Ansoft software [17, 18]. The purpose of the simulation is to optimise the gap of the B-area and the sharp angle \( \alpha \) of proportional pole shoe. The optimisation goal is to ensure that the electromagnetic force can change linearly over the gap distance of the A-area, ranging from 0.4 to 1.6 mm, as shown in Fig. 5.

Besides, it is better to increase the initial electromagnetic force of solenoid at the maximum distance. Therefore, the valve can obtain a larger initial electromagnetic force to design the higher preloaded spring force and achieve the zero-flow rate at the closed position.

### 3 Compensation with the feedforward controller

Due to the notable inductive load and hysteretic characteristics of the proportional solenoid valve, it is necessary to cooperate with the feedforward controller module and combine the relevant control algorithm to compensate for the non-linear phenomenon. That is an effective way to realise the high-precise linear control for the flow regulation in the open-loop control system. The feedforward control system [19, 20], based on the Bouc–Wen model, was adopted in the device, and the block diagram of this controller is shown in Fig. 6.

There is a severe hysteresis between the output of armature displacement and the input of current as for the proportional solenoid valve. So, the total displacement of solenoid valve armature can be regarded as the combination of a linear component and a hysteresis component, and the following model is presented as:

\[
x(t) = k_i I(t) + h(t),
\]

where \( x(t) \) is the output of armature displacement, \( I(t) \) is the input of current, \( k_i \) is the proportional ratio between the electromagnetic force and the current, and is used to describe the hysteresis component. For this hysteresis component, it is suitable to use Bouc–Wen hysteresis operator to simulate as:

\[
h(t) = aI(t) - \beta I(t)h(t) - \gamma I(t)\dot{h}(t),
\]

where \( h(t) \) is the first derivative of the hysteresis component, \( I(t) \) is the first derivative of current, and \( a, \beta, \gamma \) and \( k_i \) are all needed to solve by learning and observing the hysteresis character of the real valve in the measurement.

Taking the sinusoidal wave as a sample for the measurement, the current signals of the same period and peak value can be applied to the solenoid valve under the initial zero condition as

\[
I(t) = A \sin(2\pi f t),
\]

\[
\dot{I}(t) = I'(t) + C,
\]

where \( A \) is the amplitude of the sinusoidal current, \( f \) is the frequency of the sinusoidal current, and \( C \) is the offset component of the direct current. Therefore, the corresponding output value can be expressed as

\[
x_i(t) = k_i I(t) + h(t),
\]

\[
x_i(t) = k_i(I'(t) + C) + h(t).
\]
In this way, the output displacement of currents $I(t)$ and $I'(t)$ can be measured as $x(t)$ and $x'(t)$, respectively. Therefore, when (6) is subtracted from (5) with a group of measuring points and take the mean value, we can get

$$k_i = \frac{\sum_{i=1}^{N} (X_i - X_{i0})}{NC},$$  \hspace{1cm} (7)$$

where $N$ is the calculated number of points. At this time, $k_i$ can be identified from (7).

According to (2), when $h(t) = 0$, it can be described as:

$$h(t) = aI(t),$$  \hspace{1cm} (8)$$

$$\alpha = \frac{\sum_{i=1}^{N} i/h_{ii}}{N}. $$  \hspace{1cm} (9)$$

When $I(t) > 0$ and $h(t) > 0$ with the calculated number of points $N_1$, it can be calculated as:

$$\beta + \gamma = \frac{\sum_{i=1}^{N_1} a_i - h_i}{N_1 h_i} \left(\frac{1}{N_1} \right),$$  \hspace{1cm} (10)$$

When $I(t) > 0$ and $h(t) < 0$ with the calculated number of points $N_2$, it can be calculated as:

$$\beta - \gamma = \frac{\sum_{i=1}^{N_2} a_i - h_i}{N_2 h_i} \left(\frac{1}{N_2} \right),$$  \hspace{1cm} (11)$$

In combination with (10) and (11), we get

$$\beta = \frac{1}{2} \left[ \frac{\sum_{i=1}^{N_1} a_i - h_i}{N_1 h_i} + \frac{\sum_{i=1}^{N_2} a_i - h_i}{N_2 h_i} \right].$$  \hspace{1cm} (12)$$

Therefore, $\alpha, \beta$, and $\gamma$ can be identified according to (9), (12) and (13), respectively.

The hysteresis problem can be eliminated by identifying the parameters $\alpha, \beta$, and $\gamma$ in the Bouc–Wen model, getting a good agreement with the test results. However, the non-linear problem is difficult to be eliminated directly by only the Bouc–Wen model. So, the quadratic fitting curve, as an inverse function, is also needed in the control system, as shown in Fig. 7, so that the valve performance after feedforward compensation can meet the linear requirements better. This quadratic curve equation is obtained mainly through the simulation, the measurement and a fitting method in the test process.

### 4 Test and discussion

The proportional flow control valve is shown in Fig. 8, with a diameter of 4 mm and a working pressure of >10 MPa. Moreover, its feedforward control device for compensation shown in Fig. 9 needs a 28 V power supply to output the current directly to the valve through the power management module. Meanwhile, the digital quantity of serial port gives the control instruction. Thus, there are 256 control points ranging from 00 bytes to FF bytes, realising the digital control of valve flow with a good resolution.

According to the test result of the proportional solenoid valve, as shown in Fig. 10, the armature of the solenoid was not attracted eventually. After that, the use of the quadratic inverse function set regression analysis, the determination coefficient $R^2$ is still evident before the compensation.

Fig. 11 indicates the effect of the feedforward control device on the valve linearity. When the Bouc–Wen model was used to eliminate the problem of hysteresis, the lift curve and return curve can be forced to narrow the gap and keep in the same track eventually. After that, the use of the quadratic inverse function set in the control device can be used to realise the linearisation. After regression analysis, the determination coefficient $R^2$, which refers
to the goodness of fit, reached 0.999 in Fig. 12. This result showed that the regression line fitted the observed values in the test very well.

The mass-flow rate test was also carried out with alcohol as the test medium, to validate the linear relationship between the control points and the mass-flow rate. Given a fixed pressure drop in the experiment, the mass flow of the proportional solenoid valve was tested under the control of the compensation device. In this test, the data collection time of each point was >10 s, without any fluctuation in the flow. It showed that the position of valve armature was very stable without a shaking problem in the operation process. The test results in Fig. 13 showed the excellent linearity and repeatability with the determination coefficient $R^2$ as 0.988.

5 Conclusion

As an ideal flow regulation scheme in the propellant system of spacecraft, the proportional solenoid valve can be widely used with a distant prospect in the future. In this study, the design of the proportional solenoid valve with a compensation control device shows the excellent linearised flow control performance that can adapt to the high-load condition, which has the following characteristics:

(i) The magnetic circuit design was optimised to inhibit the excessive increment of an electromagnetic force. Meanwhile, the pressure balance structure was constructed to eliminate the pressure difference interference. This balance structure can weaken the dead zone caused by pressure difference and avoid the sudden step change to keep the balance. These designs provided the precondition for the effective compensation of the control device.
(ii) The feedforward control device for linearisation was adopted to adequately compensate the electromagnetic hysteresis and non-linear phenomenon by using the Bouc–Wen model algorithm and the quadratic inverse function. The Bouc–Wen model can narrow the gap caused by electromagnetic hysteresis, and the quadratic inverse function model can straighten up the non-linear relationship between the input current and the output displacement of the armature. Combining these two parts of the design, the goal of the proportional valve with the high linearity was achieved successfully under the digital control instructions.

6 References

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