Study on Mathematical Modeling and Response Characteristics of High-speed Solenoid Valve for Aero-engine

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Keywords: High-speed solenoid valve, Mathematical model, Response characteristics

Abstract

Because of its advantages of simple structure, fast response speed, strong anti-pollution ability and good stability, high-speed solenoid valve has been widely used in aeroengine control systems, and some performances of the aeroengine control systems were affected directly by the response speed of high-speed solenoid valve. For some two-position two-way high-speed solenoid cone-valve, the paper discusses the establishment of its mathematical model and analyses its response characteristics by simulation model which is run in simulink of Matlab. Further more, a backstepping and segmentation method is used in the research of response characteristics, and the method is proved to be an accurate, fast and new method to get the influences of parameters on the valve's response characteristics.

Introduction

In recent years, high-speed solenoid valve has been widely used in many control systems for its advantages of simple, faster response speed, stronger anti-pollution ability, higher reliability and lower price. PWM is the main input method of the valve, and the switching time of the valve can be controlled by the pulse duty factor, so is the out flow of the valve[1-3]. So the high-speed solenoid valve is prevalent as an execution component of the fuel regulation system. For a stable and reliable performance is needed to match the system, the valve must has the characteristics of strong electromagnetic force and fast response speed.

In this paper, Backstepping and segmentation method was used to analyze the mode of the valve. And this method was proved to be a new, accurate and fast method to get the influences of parameters on the valve's response characteristics. The Application of high-speed solenoid valve was also discussed.

Structure and Principle of High-speed Solenoid Valve

According to its Structure, the valve had four types of the slide-valve, the cone valve, the ball valve, and the nozzle flapper valve. The cone valve has many good characteristics, and it was the best choice for the high-speed solenoid valve. Electromagnet was one of the key parts, and ringed multi-polar solenoid was chosen for our investigation.

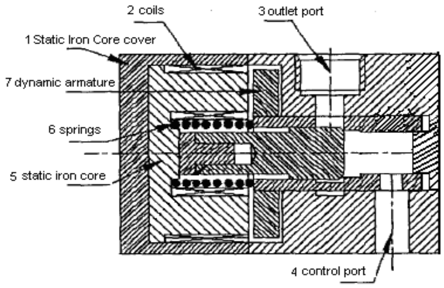

Fig.1 Structure of high-speed solenoid valve

Fig.1 showed the structure of the valve, which was a two-position two-way high-speed solenoid cone-valve which was built based on the two-position three-way valve[4]. It worked with the balance of the electromagnetic force, the hydrodynamic force and the spring force.

Valve Modeling

On the basis of theory analysis, the valve's circuit equations are denoted as.

$$e = -N\frac{d\Phi}{dt} \qquad (1)$$

$$U = Ri - ne \qquad (2)$$

where R is the equivalent circuit resistance, U is the power voltage, N is turns number, n is the pole number of the solenoid.

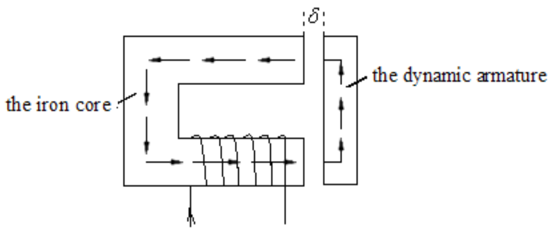

Fig.2. the unit model of the electromagnet

For the Permeability of Ferromagnetic Materials was very big ($u_{Ferromagnetic} >> u_0$), the air-gap's influence is only considered as shown in Fig.2. According to Kirchhoff's Second Law, the magnetism equation can be gained as.

$$Ni = 2\frac{\Phi}{u_0 S_x}\delta \qquad (3)$$

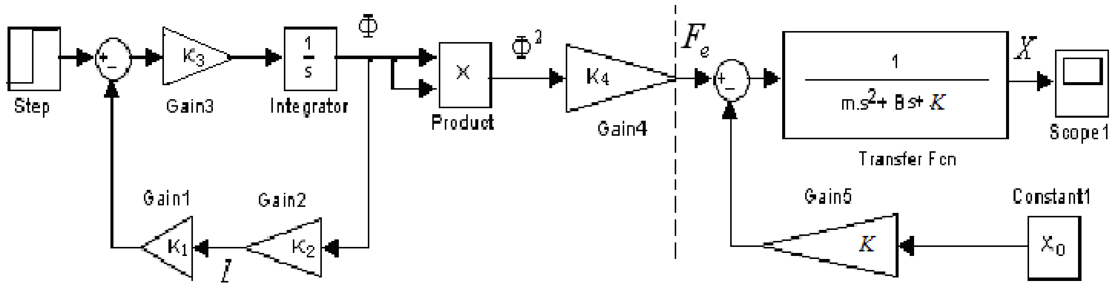

Fig.3 The block diagram of the high - speed solenoid valve

where u_0 is the air-gap's permeability, δ is the air-gap's width which could be regarded as the valve's stable operation width in simplification, and S_x is the air-gap's area of the "E" loop.

Considering n magnetic poles of the solenoid, inductance coiler suction can be gained from the Maxwell's Electromagnetic Force Equation as follow.

$$F_e = nF_{e_0} = \frac{n^2\Phi^2}{2u_0 S_0} \qquad (4)$$

On the other hand, the motion equation can be expressed as.

$$F_e == m\ddot{x} + B\dot{x} + K(x + x_0) \qquad (5)$$

where m is the mass of the dynamic armature, B is the sum of the transient flow coefficient and the viscosity damping coefficient, K is the sum of the spring's stiffness and the steady-state coefficient, x is the displacement of the dynamic armature, x_0 is the spring camber with pre-tightening force.

Simulation and Analysis of the Valve

Simulink of Matlab is an effective emulation tool with the characteristics of fast, accuracy and convenience.

Based on the circuit equations as (1) and (2), the magnetism equations as (3) and (4), and the motion equation as (5), the block diagram of the high - speed solenoid valve was gained as shown in Fig.3. There were the following parameter definitions.

$$K_1 = R \qquad (6)$$

$$K_2 = \frac{16\delta}{Nu_0 S_0} \qquad (7)$$

$$K_3 = \frac{1}{8N} \qquad (8)$$

$$K_4 = \frac{32}{u_0 S_0} \qquad (9)$$

System analysis

As shown in Fig.3, the system is composed of two series parts. The system's input is the step voltage, and the output is the displacement of the dynamic armature.

The part of the left was gained from the circuit equations and the magnetism equations above, which is a feedback control which has the characteristic of high precision. The part of the right was gained from the motion equation above, which is an open-loop control whose output has no influence on the system. The interaction of these two parts could meet the system's requirements of fast response and good reliability.

So we should choose a backstepping and segmentation method to analyze the two parts separately.

Second-Order Open-loop Control

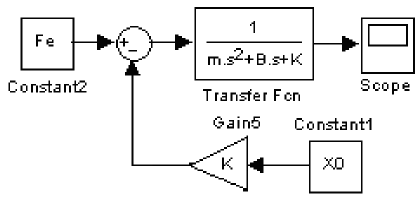

Fig.4 The block diagram of the second order open-loop control

Fig.4 shows the block diagram of the second order open-loop control, so its transfer function could be gained as follow.

$$G(s) = \frac{1/m}{s^2 + \frac{B}{m}s + \frac{K}{m}} \qquad (10)$$

The damping ratio and the natural frequency were as follows.

$$\varsigma = \frac{B}{2\sqrt{mK}} \qquad (11)$$

$$\omega_n = \sqrt{\frac{K}{m}} \qquad (12)$$

In the underdamping system, the rise time decreased as the damping ratio decreasing and the natural frequency increasing. From (11) and (12), it was found that K and m interacted with each other.

The design indexes of rising time and overshoot were as follows.

$$t_r = \frac{\pi - \arccos\varsigma}{\omega_n * \sqrt{1-\varsigma^2}} = 0.006 \qquad (13)$$

$$\sigma\% = e^{-\pi\varsigma / \sqrt{1-\varsigma^2}} * 100\% = 2\% \qquad (14)$$

According to the design indexes, the damping ratio and the natural frequency were gained as follows.

$$\varsigma \approx 0.7797 \qquad (15)$$

$$\omega_n = 656.12 rad/s \qquad (16)$$

Adjusting time equation was as the following with the overshoot is 2%.

$$t_s = \left[4 - 0.5\ln\left(1-\zeta^2\right)\right] / \zeta\omega_n = 8.7ms \qquad (17)$$

From (11), (12) and the dynamic armature's mass, we got K and B as follows.

$$K = 8.6099 N/mm \qquad (18)$$

$$B = 20.46 kg/s \qquad (19)$$

Because of the limitation of the air-gap's width between the outer sleeve and the dynamic armature and the requirements of the dynamic armature's displacement and the spring's initial camber, it could meet the requirements on the premise of $F_e = 35N$.

The response curve is shown in Fig.5.

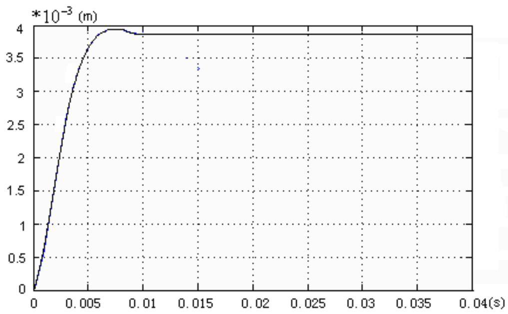

Fig.5 The simulation curve of the second order open-loop control

As shown in Fig.5, the simulation results were approximately equal to the calculation results, including the response time, the dynamic armature's displacement and the electromagnetic force. $x \approx 3.865mm$, $F_e = 35N$.

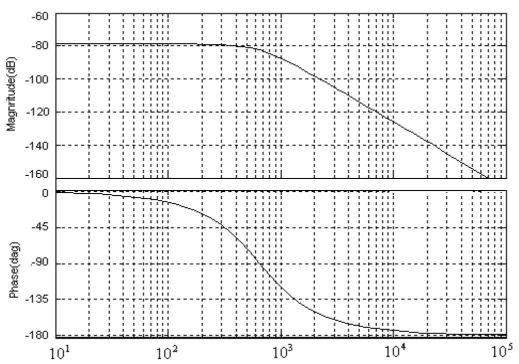

Fig.6 the bode diagram of the second order open-loop control

The bode diagram of the second order open-loop control could be expressed as shown in Fig.6, so this part was stable.

First-order open-loop control

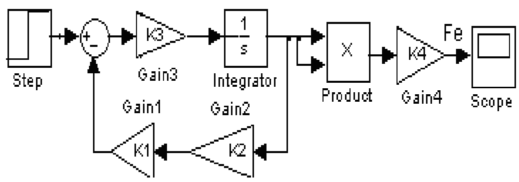

Fig.7 The block diagram of the first-order closed-loop control

Fig.7 shows the block diagram of the first-order closed-loop control. As shown in Fig.7, K_4 is only related with the air gap's cross sectional area, so K_4 is a fixed value with the air gap's cross sectional area fixed.

The transfer function of the closed-loop part and the time constant are as follows.

$$G(s) = \frac{1/K_1K_2}{s/K_1K_2K_3 + 1} \qquad (20)$$

$$T = \frac{1}{K_1K_2K_3} = \frac{N^2 u_0 S_0}{2\delta R} \qquad (21)$$

And the response time decreased with the time constant decreasing.

The displacement of the dynamic armature was $3.865mm$, so the air gap's width was $(\delta_0 - 3.865)mm$, and δ_0 was the air gap's initial width.

Assuming three parameters of δ_0, N and R were fixed, then changing the third one, the simulation curves with different parameters were gained. Then we found that the response time could be decreased through decreasing N, increasing R and δ_0. Besides, the response time decreased with the air gap's cross sectional area decreasing.

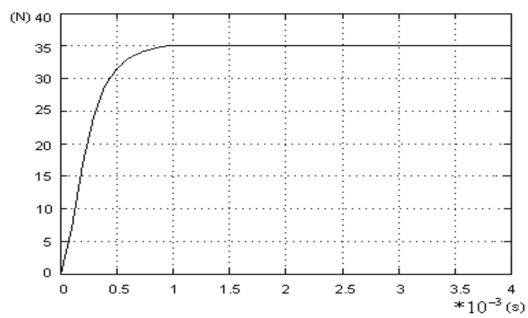

Fig.8 Simulation curve of the first-order closed-loop control

Combining the second-order open-loop control, parameters' data of this part were gained from simulation. $N = 20$, $R = 51.464\Omega$, $T = 1.6897*10^{-4} s$. Fig.8 shows the simulation curve of this part, and its response time is less than 1ms.

Simulation and analysis of the whole system

Combining the two parts above and making a data substitution of the Fig.3, the simulation curve of the whole system was shown in Fig.9.

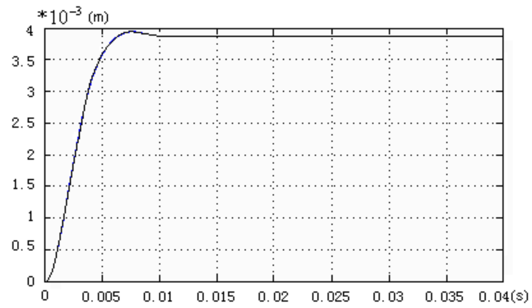

Fig.9 simulation curve of the whole system

As shown in Fig.9, the response time is less than 10ms. Besides, the response time mainly depended on the second-order open-loop.

Conclusions

The influence of N , δ , R and other parameters on the response time of high-speed solenoid valve was analyzed in this paper, and the research result shown that these parameters were interacted with each other. So, they should be considered comprehensively in order to get the best result. Besides, this paper was on the basement of a fixed driving voltage, but the driving voltage also had large influence on the response time of the valve. The response time decreased with the driving voltage increasing. In real application, overvoltage was used with the aim of decreasing the response time.

Backstepping and segmentation method used in this paper was a new method for studying the characteristics of the high-speed solenoid valve. It had the advantages of simple, effective and convenient.

In real application, a new flow-controllable actuator can be constructed on the basement of combining a high-speed solenoid valve with a gear hydraulic motor. The high-speed solenoid valve is used to control the in-flow of the gear hydraulic motor, so the output of the actuator can be more stable and accurate, and the actuator's application can also be enlarged. The performance of the flow-controllable actuator is largely decided by the characteristics of the valve, so parameter optimization and structure optimization of the valve can help to improve the actuator's performance.

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