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A STUDY OF ON/OFF SOLENOID ACTUATOR WITH POWER SAVING CIRCUIT

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ABSTRACT

The technology of on-off solenoid valves is now considered as a core technology in the fields of the production line of semi-conductor chips and the micro fluid chips for medical applications. And on-off solenoid valves, which operate by compressed air, are characterized by high speed response, great repeatability and that the pressure on the cross sectional area of poppet is kept constant regardless of the fluctuation of the pressure exerted on the ports. The primary objective of this study is to compare the optimally designed solenoid valve with the actually produced one and to design a power saving circuit which can highly improve the efficiency by providing optimal current according to mechanical load. The power saving circuit can be adopted into the 0.35Watt micro valve which has been developed through this study and lower the power consumption of the valve to 0.1Watt. The absorbing force at 0.3mm stroke, the initial stroke of Plunger and Core, is very large. But the absorbing force at 0mm stroke when Plunger and Core are tightly stuck to each other is several newtons lower than that at the initial stroke, the valve still performs stable and flawless though. It means that with lower current consumption, it still performs stable. Based on that, we've designed the power saving circuit.

KEY WORDS

Micro valve, Solenoid, Power saving circuit, Design, High speed response, Great repeatability

INTRODUCTION

Recently, as new computer systems and various controlling technologies are being developed, on-off solenoid valves are able to be more precisely controlled and the application areas, including semi-conductor chip mounter, electronics production line, bearing auto-transmission line, injection molder, fatigue and vibration tester and etc., are getting diverse. Especially, the technology of on-off solenoid valves is now considered as a core technology in the field of technology-intensive process development such as semiconductor industry, and many studies are being conducted to design ones meeting the basic requirements for the improvement in the aspects of high performance, low price, long life-time, high reliability and ergonomics and the compatibility with the environment[1].

In this study, we carry out the optimal design and modeling of a on-off solenoid valve and analyze it using Maxwell, a commercial analysis program, and then, after actually producing the valve, demonstrate the feasibility of its optimal design by comparing the simulation data of its optimal design with the data of its actual product.

Besides, we design a power saving circuit which can be adopted into the 0.35Watt micro valve which is developed through this study and lower the power consumption of the valve to 0.1Watt.

STRUCTURE & OPERATING MECHANISM

Figure 1 shows a schematic diagram of a micro valve. The major components of a micro valve include poppet which controls the direction of compressed air, plunger, stationary core and spring, o-ring which prevents leakage and gasket.

The basic operating mechanism of micro valves is as follows: when turn on the current in solenoid, poppet moves forward by the electromagnetic power and compressed air starts to flow from supply port to pressure port and when turn off the current in solenoid, poppet moves backward by spring force and supply port closes and the air is then expelled out of exhaust port. Based on this mechanism micro valves perform high speed reciprocating movement.

Table 1 shows the design specification and performance specification of the micro valve designed in this study.

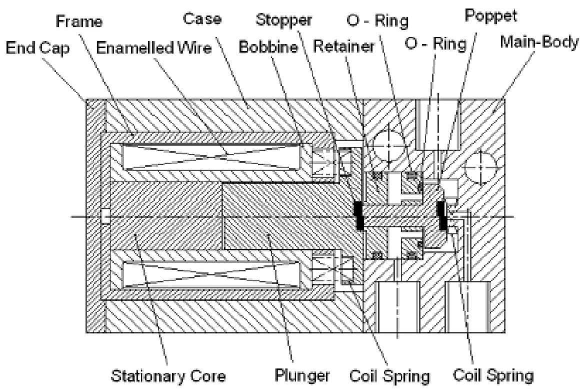


Figure 1 Schematic Diagram of Micro Valve

Table 1 Design Specification

Item	Value	Unit
Supply Pressure	3	bar
Supply Voltage	24	V
Electric Power	0.3	W
Port	3	㎜
Stroke	0.3	㎜
Coil Turn Number	6,500	turn
Coil Diameter	0.04	㎜
Coil Resistance	1.5	kΩ
Response Time	2	㎳
Temperature Rise Value	50	℃
Magnetic Force	4.3	N
Spring Constant	0.015	N/㎜

DESIGN THEORY AND MAGNETIC FIELD ANALYSIS OF SOLENOID VALVE

Solenoid Design Theory

The two key technologies for micro valves are solenoid technology and poppet technology. As for solenoid design, a field analysis is the most important factor. The absorbing force(F) induced by solenoid can be obtained from the eq. (1)[2~3].

$$F = \frac{B_g^2 S}{2\mu_0} = \frac{10^7}{8\pi} B_g^2 S[N] \quad (1)$$

where B_g is the air gap flux density by permanent magnets, and μ_0 is the magnetic permeability.

From the eq. (1), the cross-sectional area of the movable element (S) can be expressed as the eq. (2).

$$s = \frac{8\pi \times 10^7 \cdot F}{B_g^2} \ [\text{m}^2] \quad (2)$$

The radius of the movable element (γ_1) can be calculated by $\gamma_1 = \sqrt{(2\mu_0 F)/\pi B_g^2}$ and the magnetomotive force (U) can be obtained from the eq. (3).

$$U = NI = \frac{B_g l_g}{\mu_0} + \sum H_l l_l \ [A] \quad (3)$$

The following eq. (4) show the correlations among the value determining the coil space (h), temperature (T), temperature rise values (θ_f and θ_{fi}).

$$\theta_f = (I^2 R)/(2\lambda l_m h) \ [℃]$$

$$\theta_{fi} = (qp/2\lambda\xi T)\cdot(NI/h)^2 \ [℃] \quad (4)$$

where θ_f is final temperature rise value, θ_{fi} is continuous certain temperature rise value, and NI is the width of the coil (h/β) .

From the eq. (4), the height of the coil (h) can be expressed as the eq. (5).

$$h = 3\sqrt{\frac{q\beta pU^2}{2\lambda\xi\theta_f}} \quad (5)$$

where q is time rating, p is copper wire resistivity, λ is coil's thermal diffusivity coefficient, and ξ is coil's space factor.

The internal and external diameters of the coil ($r_1^{'}, r_2^{'}$) should be determined. Since the internal diameter ($r_1^{'}$) is determined by the external diameter of movable element plus coil's clearance plus Bobbin's thickness, $r_2^{'} = r_1^{'}$ +T and V=IR, then we can derive the eq. (6).

$$V = \frac{4p(\mathrm{r}_1^{'} + \mathrm{r}_2^{'})\mathrm{NI}}{\mathrm{d}^2} \quad [\mathrm{V}] \qquad (6)$$

Therefore, the wire diameter of the coil (d) can be obtained from the eq. (7).

$$d = \sqrt{4p(\mathrm{r}_1^{'} + \mathrm{r}_2^{'} \cdot \frac{NI}{V})} \quad [\mathrm{mm}] \qquad (7)$$

Thus, the number of coil layers (m) and the coil turn number (N) can be calculated from $m = T/d$ and $N = ((h/d)-1)m$, respectively.

For temperature rise value, exciting current (I_h) should be previously determined. The mean length (l_m) and the total length (l_t) of the coils can be calculated from the eq. (8).

$$l_m = \pi(2r_1 + T), \quad l_t = Nl_m \qquad (8)$$

The coil resistance at 20 ℃ = $l_t \times$ resistance coefficient, the coil resistance at 100℃ $= 1.314 \times R_c$, exciting current $I_h = V/R_h$, and magnetomotive force $U = NI_h$. Therefore, temperature rise value is determined by θ_f.

Solenoid Modeling and Analysis Results

In order to analyze the solenoid part of the micro valve, we conducted the solenoid modeling as shown in Figure 2. Figure 2 ~ Figure 6 shows the analysis results about the static and dynamic characteristics of the micro valve by the solenoid. Figure 2 ~ Figure 6 indicate that it starts to operate at 2ms.

As you can see in Figure 6, the overall changes in the current can be largely divided into 3sections: A, B and C. In A section, the movement of the plunger is very little and the current is increasing. In B section, the movement of the plunger is getting faster and the current is decreasing. And C section indicates the state after the movement of the plunger is done.

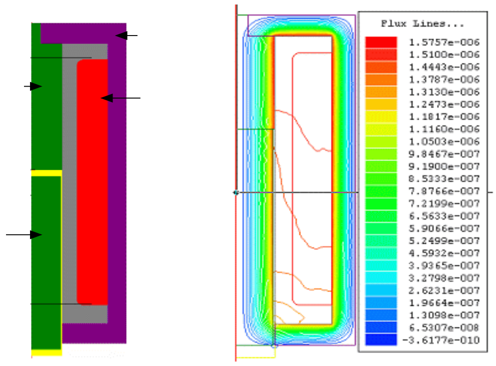


Figure 2 Modeling of Solenoid

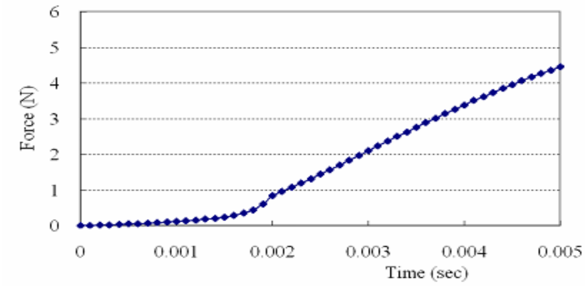


Figure 3 Force vs. Time

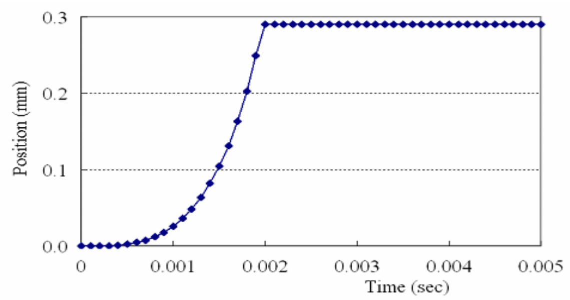


Figure 4 Position vs. Time

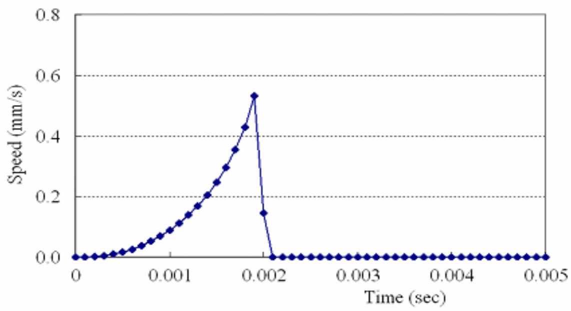


Figure5 Speed vs. Time

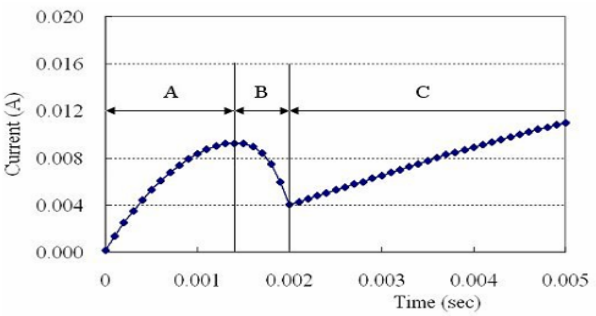


Figure 6 Branch Current

EXPERIMENTATION OF ON-OFF MICRO VALVE

Development of Solenoid Valve

Based on the solenoid modeling above, we produced an actual micro valve as shown in Figure 7. Besides, in order to determine the performance of the actual micro valve, we developed the performance testers as shown in Figure 8.

Figure 7 Micro Valve Parts

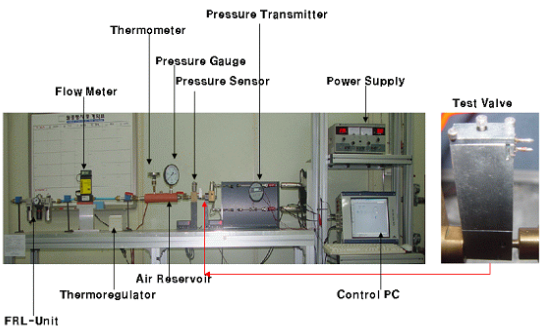


Figure 8 Performance Testers

Micro Valve Tests

Table 2 lists the results of the performance tests of the micro valve that we actually produced in this study and they are found to be similar to the results from the previous Maxwell simulation.

Table 2 Performance Tests

Item	Value	Unit
Supply Pressure	3	bar
Supply Voltage	23	V
Electric Power	0.345	W
Port	3	㎜
Stroke	0.3	㎜
Coil Turn Number	6,700	turn
Coil Diameter	0.04	㎜
Coil Resistance	1.6	kΩ
Response Time	3	㎳
Temperature Rise Value	50	℃
Magnetic Force	3	N
Spring Constant	0.015	N/㎜

Reliability Test of Micro Valve

Figure 9 shows the result of the surge current test and surge current occurs by the effect of different types of load such as voltage and power. If the open-and-close motion due to such mechanical characteristics is repeated several times, the same response concurrently occurs when ON/OFF is repeated. [4]

Figure 10 shows the result of the magnetic force test which was conducted by determining the force on the plunger with load cell after supplying the solenoid DC24V power and moving the plunger downward and upward. As the result, about 3Nof absorbing force was observed to be occurring.

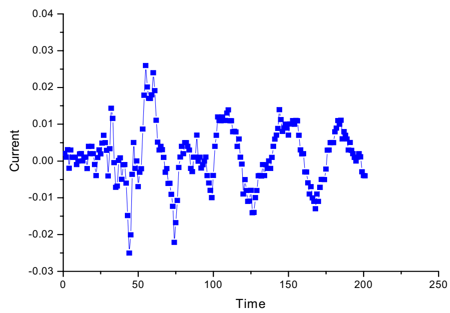


Figure 9 surge current

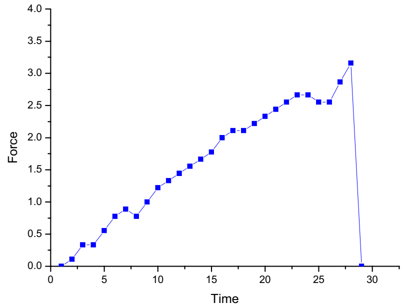


Figure 10 Magnetic Force Test

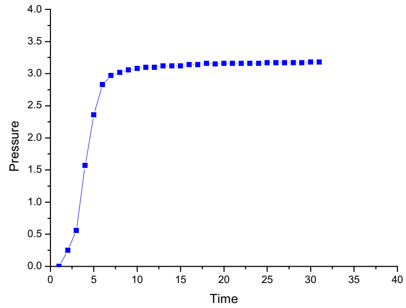


Figure 11 Dynamic Response Test

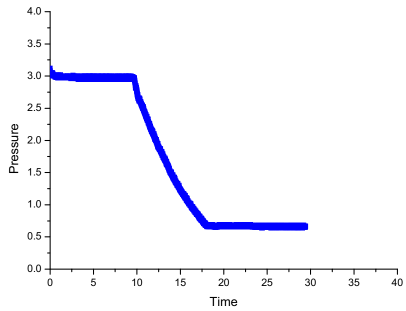


Figure 12 Flow Capability Test

Figure 11 illustrates the graph of the test results of the dynamic response and demonstrates the fast dynamic response by showing that it takes 3m for the pressure on the bottom to lift up to 80% of 3bar after opening the valve.

Figure 12 shows the results of the flow capability test which was performed under the condition of 3kgf/cm2 operating pressure after opening the valve. This graph illustrates that the pressure decreases from 3(bar) at 11.4(s) to 0.62(bar) at 20.16(s). That is to say, it takes 8.76(s) for the pressure to decrease from 3(bar) to 20% of it, 0.62(bar). The effective cross-sectional area(S) is 0.1mm2 and Cv is 0.0059.

MICRO VALVE WITH POWER SAVING CIRCUIT

Power Saving Circuit Design

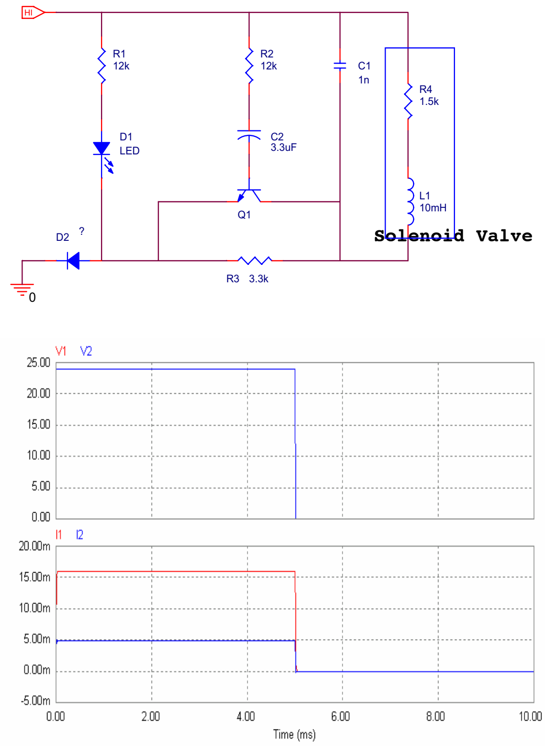


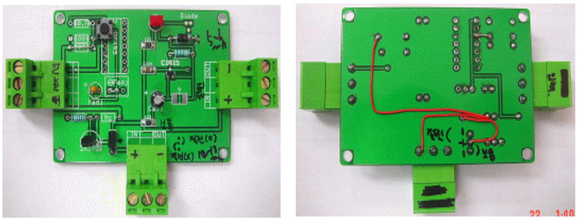
Figure 13 Power Saving Circuit Diagram

This power saving circuit can be adopted into the 0.35Watt micro valve which has been developed through this study and lower the power consumption of the valve to 0.1Watt.

. The absorbing force at 0.3mm stroke, the initial stroke of Plunger and Core, is very large. But the absorbing force at 0mm stroke when Plunger and Core are tightly stuck to each other is several newtons (N) lower than that at the initial stroke, the valve still performs stable and flawless though. It means that with lower current consumption, it still performs stable. Based on that, we've designed the power saving circuit.

For the valve without the power saving circuit (V1, I1), with 24V input, 15mA current flows in the coil. However, for the valve with the power saving circuit (V2, I2), approximately 5mA current flows in the coil and the current can be controlled by adjusting the element values

Power Saving Function Test of Power Saving Circuit



(a) the front side of the power saving circuit

(b) the rear side of the power saving circuit

Figure 14 Power Saving Circuit

Table 3 Comparison between Micro Valves With and Without the Power Saving Circuit

Case	Power (V)	current (A)	Power Consumption (Watt)
24V	23	0.015	0.345
24V with the power saving circuit	23	0.0045	0.1035

The power consumptions in Table 3 were calculated after determining the current when the plunger and the core were close to each other. From Table 3, we can see that the power consumption decreased from 0.345 Watt to 0.103 Watt.

CONCLUSION

In this study, we evaluated the performance of ultra power saving type pneumatic on-off micro valves through characteristic analysis and experiments and obtained the results as follows:

1. We designed a micro valve using the equivalent magnetic circuit method and analyzed it using Maxwell program and then, after actually producing the micro valve, demonstrated the feasibility of its optimal design by comparing the simulation data of its optimal design with the data of its actual product. As the result, the data of its actual product was found to be similar to the data of its optimal design.
2. It was demonstrated that strong enough electromagnetic force (3N) was exerted on the solenoid for the poppet to have the initial stroke (0.3mm) as high speed response (3ms) and any electromagnetic force was not emitted outside by yoke.
3. We equipped the 0.35Watt micro valve that we produced in this study with the power saving circuit and then calculated the power consumption by supplying power and determining the current when the plunger and the core were close to each other (i.e. at 0mm stroke). As the result, it was demonstrated that the power consumption decreased from 0.345 Watt to 0.103 Watt.

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