

Optimal Design and Development of Electromagnetic Linear Actuator for Mass Flow Controller

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In this paper, we constructed the analytic model of control valve as a function of electric and geometric parameters, and analyzed the influence of the design parameters on the dynamic characteristics. For improving the dynamic characteristics, optimal design is conducted by applying sequential quadratic programming method to the analytic model. This optimal design aims to minimize the response time and maximize force efficiency. By this procedure, control valve can be designed to have fast response in motion.

Key Words : Electromagnetic Linear Actuator, Optimal Design, Control Valve, Mass Flow Controller

Nomenclature

A	: Area of air gap	λ	: Flux linkage
d_c	: Coil diameter	μ_0	: Permeability of air
F_{emag}	: Electromagnetic force	ρ	: Resistivity of coil
g	: Gravitational constant		
i	: Current of coil winding		
K_p	: Proportional constant		
K_s	: Spring constant		
L_e	: Inductance of the external circuit		
l_c	: Average one turn length of coil		
m_p	: Mass of the plunger		
n	: Turn of coil		
R	: Resistance of coil		
R_m	: Magnetic reluctance		
T_c	: Temperature of coil		
T_{sum}	: Sum of rising and falling time		
V	: Applied voltage		
v	: Velocity of plunger		
W_1, W_2	: Weighting factor of cost function		
x_g	: Air gap length		
x_p	: Minimum stroke of plunger		
ϕ	: Flux		

1. Introduction

Many semiconductor processes require that stable and known flow of gas is delivered to the processing chamber. The mass flow controller (MFC) has been used wherever accurate measurement and control of gas is required (Hinkle and Mariano, 1991). This MFC consisted of three devices as shown in Fig. 1: a flow meter for the measurement of flow, a control valve to control the flow, and a controller. The control valve is constructed with electromagnetic linear actuator and actuated according to control signal given by controller to eliminate the difference between the measured flow rate and the set flow rate. The fast response of control valve depends on dynamic characteristics and electromagnetic configuration. To control precisely the mass flow rate of process gas, control valve is required to have fast response in motion. These requirements can be satisfied by optimal design of control valve.

In this paper, we constructed the analytic model of control valve as a function of electric and geometric parameters, and analyzed the influence

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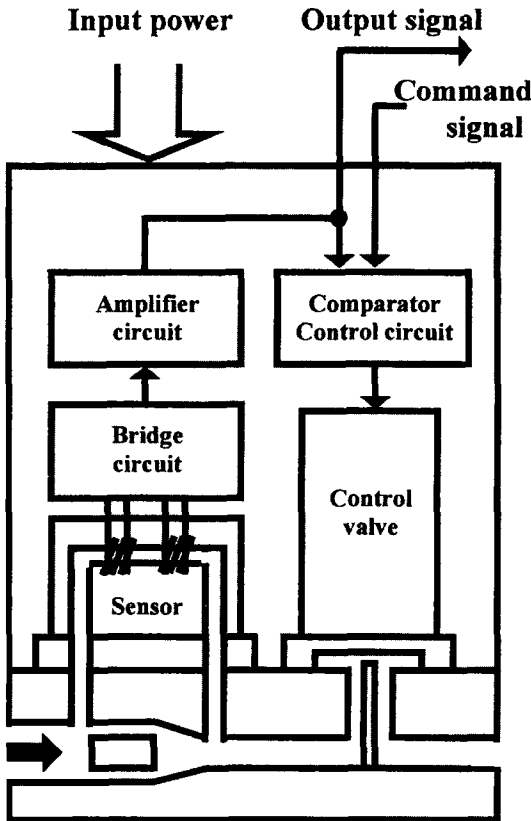


Fig. 1 Configuration of the mass flow controller

of the design parameters on the dynamic characteristics. For improving the dynamic characteristics, optimal design is conducted by applying sequential quadratic programming (SQP) method to the analytic model (Grace, 1990). This optimal design method aims to minimize the response time and maximize force efficiency.

From this work, influence of design parameters is described and optimal design is conducted with these design parameters. By this procedure, control valve is designed with fast response in motion. This control valve can be used in the high-end applications in which precise control over the movements of the actuator is required.

2. Analysis of Design Parameters

Figure 2 shows the structure of an electromagnetic control valve. The plunger of control valve retracts upward when the coil is energized,

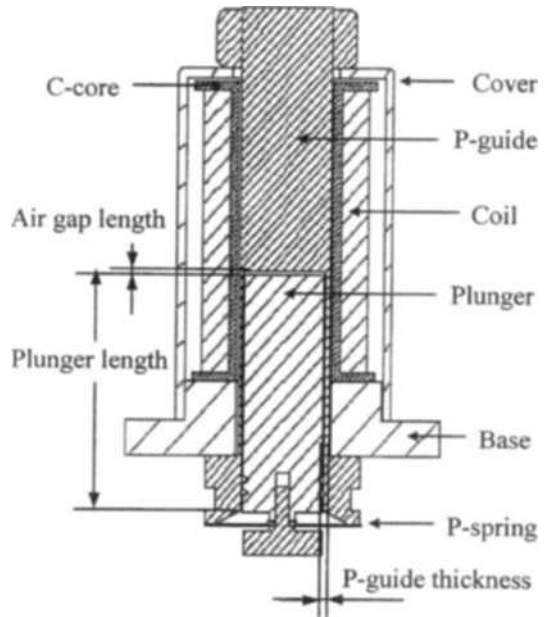


Fig. 2 Structure of the electromagnetic control valve

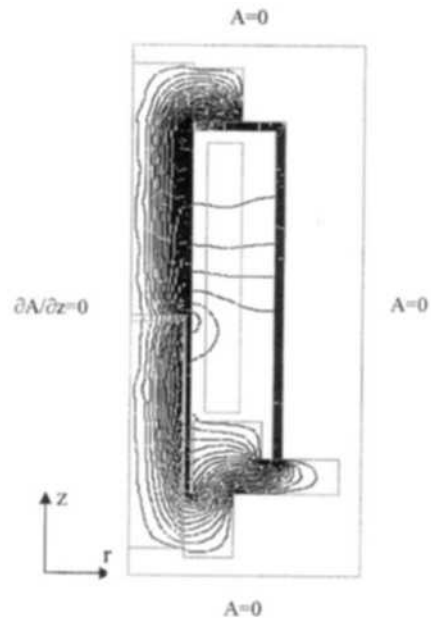


Fig. 3 Cross section model used in FEA and flux path

and extends downward by releasing the stored energy from the plate spring. Total stroke of the plunger is very short - below the several hundred micrometers. In order to achieve high force efficiency, most control valves is operated in the

non-linear magnetic saturation region. The design parameters of control valve are electrical and geometrical components. To achieve the fast response, electromagnetic force has to be maximized. The design parameters related with electromagnetic force are coil diameter, plunger length, air gap length, and p-guide thickness. Influence of each design parameter is simulated by using Finite Element Analysis (FEA). Figure 3 shows the cross section model used in FEA and flux path. Since the control valve has the axis-symmetric structure, we used half of the cross section as shown in Fig. 3.

2.1 Effect of coil diameter

In electromagnetic actuator, the current flowing in coil is a source of electromagnetic force. This current is related with coil diameter under fixed applied voltage. The relationship is given by

$$ni = n \frac{V}{R} = K_p \frac{V d_c^2}{\rho l_c} \quad (1)$$

where, n is a turn of coil, i is a current of coil winding, V is an applied voltage, R is a resistance of coil, K_p is proportional constant, ρ is resistivity of coil, l_c is an average one turn length of coil, d_c is a coil diameter.

From Eq. (1), current is proportional to coil diameter. Also electromagnetic force is proportional to coil diameter.

2.2 Effect of plunger length

The plunger is used as a path of electromagnetic flux generated by coil, so magnetic flux is changed according to plunger length.

By using FEA, the flux density distribution according to plunger length is obtained. The electromagnetic force acting on plunger according to plunger length is listed in Table 1.

Table 1 Electromagnetic force according to plunger length

	Plunger length (mm)			
	20	25	30	35
Electromagnetic force (N)	11.88	12.86	13.27	13.14

2.3 Effect of air gap length

The air gap used as the space for stroke of plunger is a resistance of electromagnetic circuit (Hanselman, 1994). The relationship of air gap length and electromagnetic flux is given by

$$\phi = \frac{ni}{R_m} = \frac{ni}{x_g / \mu_0 A} \quad (2)$$

where, ϕ is a flux, R_m is a magnetic reluctance, x_g is an air gap length, μ_0 is a permeability of air, and A is an area of air gap.

The air gap length is minimized under designed stroke for maximizing the flux, which is maximizing the electromagnetic force.

2.4 Effect of p-guide thickness

The p-guide is used as guide of plunger motion. For maximizing the electromagnetic flux flowing to plunger, flux flowing through the p-guide has to be minimized.

By using FEA, the electromagnetic force acting on plunger according to p-guide thickness is obtained and listed in Table 2.

From each simulation, the effects of each design

Table 2 Electromagnetic force according to p-guide thickness

	P-guide thickness (mm)		
	0.25	0.50	1.00
Electromagnetic force (N)	14.37	12.86	7.67

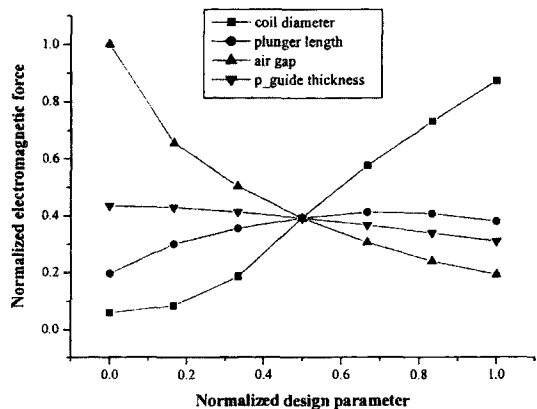


Fig. 4 Relationship between electromagnetic force and design parameters

parameters on electromagnetic force are analyzed and are showed in Fig. 4, where the normalized design parameters are obtained with six same divisions between minimum and maximum value of each design parameters. Each normalized electromagnetic force is calculated according to change of one design parameter value with fixed center values of other design parameters. In this simulation, air gap length and p-guide thickness is limited to minimum value and coil diameter is limited to maximum value in the condition of without constraints. In design of control valve, there are many constraints. So the design parameters are obtained from the optimal design under the constraints.

3. Dynamic Characteristics

Control valve has a resistive and inductive structure. Its voltage equation can be expressed as :

$$V = Ri + \frac{d\lambda}{dt} \quad (3)$$

where, λ is a flux linkage and a variable dependent on the current of the coil and the air gap length x_g . So the voltage equation can be rewritten as :

$$V = Ri + \left(L_e + \frac{\partial \lambda(x_g, i)}{\partial i} \right) \frac{di}{dt} + \frac{\partial \lambda(x_g, i)}{\partial x_g} \frac{dx_g}{dt} \quad (4)$$

where, L_e is the inductance of the external circuit. Eq. (4) can be solved if the magnetic characteristics of the control valve are known.

The moving part of control valve can be represented by a mass and spring system, as follows :

$$m_p \ddot{x}_g + K_s x_g = F_{emag} - m_p g \quad (5)$$

where, m_p is the mass of the plunger, K_s is the spring constant, g is the gravitational constant, and F_{emag} is the force produced by electromagnetic flux when the coil is energized. F_{emag} can be calculated from the co-energy (Krause, 1986) (see Appendix 1).

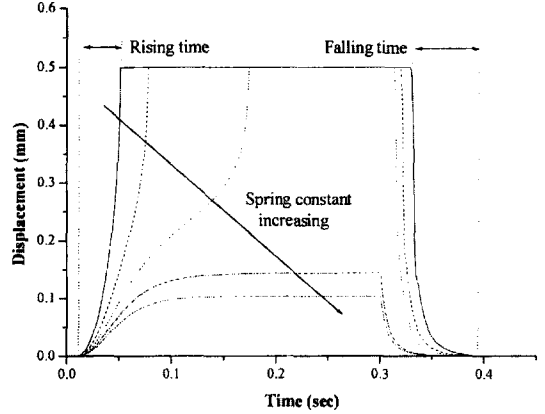


Fig. 5 Dynamic response of control valve according to spring constant

From Eq. (3) ~ (5), dynamic characteristics of control valve is obtained and represented as state equations :

$$\frac{dx_g}{dt} = v \quad (6)$$

$$\frac{dv}{dt} = (F_{emag} - K_s x_g - m_p g) m_p^{-1} \quad (7)$$

$$\frac{di}{dt} = \left(V - Ri - E(x_g, i) \frac{dx_g}{dt} \right) L(x_g, i)^{-1} \quad (8)$$

where, v is velocity of plunger, $E(x_g, i) = \frac{\partial \lambda(x_g, i)}{\partial x_g}$ and $L(x_g, i) = L_e + \frac{\partial \lambda(x_g, i)}{\partial i}$.

Using Eq. (6) ~ (8), dynamic response of the control valve is simulated according to spring constant and the results are shown in Fig. 5, where the stroke of plunger is limited to 0.5 mm.

4. Optimal Design Method

The SQP is used for optimal design of control valve. This method uses an iterative procedure, and generates a quadratic programming sub-problem at each iteration, and updates the estimate, which is the Hessian of Lagrangian.

From Eq. (6) ~ (8), we know that the dynamic characteristics are related with electric and geometric parameters. So these parameters affecting the dynamic characteristics are selected as design variables, and the other parameters are selected as fixed variables.

Table 3 Optimized values of design variables

Item	Value	Unit
Coil diameter	0.205	mm
Plunger length	25.1	mm
Air gap length	0.5*	mm
P-guide thickness	0.5*	mm
Spring constant	12.17	kN/m

* : Active bounded

The optimal design method aims to minimize the response time and maximize force efficiency. The cost function is given by

$$J(x) = W_1 * T_{sum} + W_2 * (F_{emag} / V) \quad (9)$$

where, W_1 and W_2 are weighting factor of cost function and set as 0.5, respectively, T_{sum} is a sum of rising and falling time as shown in Fig. 5, x is a design variables.

The design variables are selected such as coil diameter, plunger length, air gap length, p-guide thickness, and spring constant. And fixed variables are applied voltage, coil winding area, plunger diameter, etc.

The constraints are the minimum stroke of plunger x_p , temperature of coil T_c (see Appendix 2), and the first natural frequency f_1 . The constraint conditions are given by

$$g_1(x) = G_1 - x_p \leq 0 \quad (10)$$

$$g_2(x) = T_c - G_2 \leq 0 \quad (11)$$

$$g_3(x) = G_3 - f_1 \leq 0 \quad (12)$$

where, $G_1=0.5$ (mm), $G_2=80$ ($^{\circ}$ C), $G_3=100$ (Hz).

We set initial value of design variables as the middle of bounded value, and convergence tolerance as 0.01%.

Table 3 lists the values of optimized design variables of control valve. As shown in Fig. 4, air gap length and p-guide thickness are bounded to low limit. But coil diameter is converged to optimal value.

5. Experimental Results

The control valve is constructed with optimized design values. The electromagnetic force according to applied voltage is calculated by using the

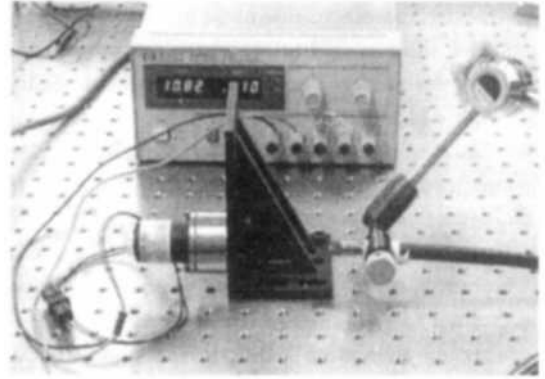


Fig. 6 Experimental setup and constructed control valve

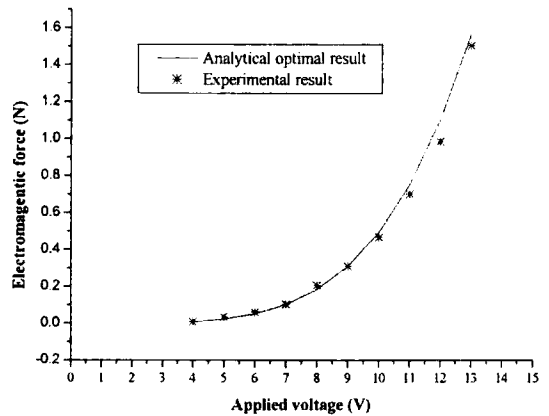
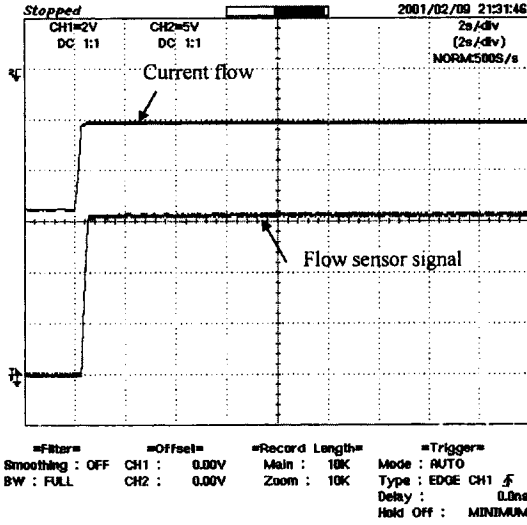
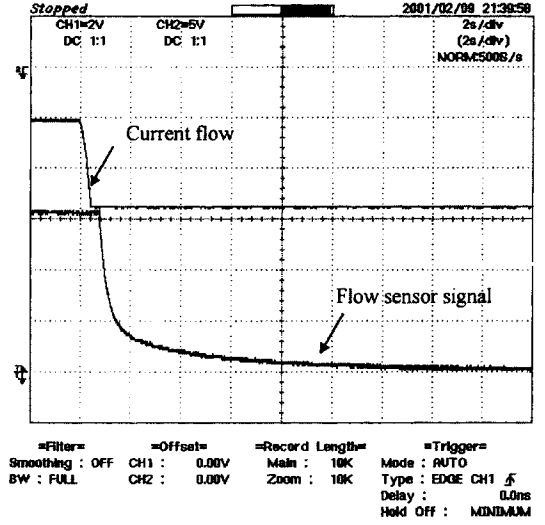


Fig. 7 Comparison of electromagnetic force according to applied voltage between the analytical optimal design and experiment

spring constant and deflection of spring, where deflection is measured by laser vibrometer as shown in Fig. 6. The comparison of electromagnetic force according to applied voltage between the analytical optimal design and experiment is shown in Fig. 7, where the difference comes from modeling error or manufacturing tolerance of control valve. This means that the constructed control valve does not optimal, but almost optimal. The response time of optimal designed control valve is shown in Fig. 8, where Fig. 8 (a) shows a rising time from closed to full open state and Fig. 8 (b) shows a falling time from full open to closed state.



(a) Rising time



(b) Falling time

Fig. 8 Response time of optimal designed control valve

6. Conclusions

From the construction of the analytic model of control valve, the analysis of the influence of the design parameters on the electromagnetic force, the optimal design of control valve, and experiment of dynamic responses, we can list the following conclusions.

(1) The dynamic response of control valve can be calculated in the function of electric and geometric parameters.

(2) The design parameters of control valve having the maximum electromagnetic force and minimum response time under constraints can be obtained from the optimal design.

(3) In spite of difference between analytic optimal design and experiment, the optimal design of the control valve is useful to improve the dynamic characteristics.

This control valve can be used in the high-end applications in which precise control of the actuator is required.

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Appendix

A.1

In the single-excited electromagnetic system, the energy and co-energy stored in a magnetic field is described with current and flux linkage as shown in Fig. A1. The co-energy is expressed as

$$W_c(x_g, i) = \int \lambda(x_g, i) di = \int L(x_g, i) idi \quad (A1)$$

where, $\lambda(x_g, i)$ is a flux linkage, $L(x_g, i)$ is a inductance of the electromagnetic system, respectively.

Electromagnetic force obtained by derivation of co-energy stored in a magnetic field of electromagnetic system is expressed as

$$\begin{aligned} F_{emag}(x_g, i) &= \frac{\partial W_c(x_g, i)}{\partial x_g} \\ &= \frac{\partial}{\partial x_g} \left\{ \int L(x_g, i) idi \right\} \end{aligned} \quad (A2)$$

To calculate electromagnetic force of electromagnetic control valve, inductance is calculated from magnetic circuit model as shown in Fig.

A2. The inductance from definition is expressed as

$$L(x_g, i) \frac{\partial \lambda(x_g, i)}{\partial i} = \frac{\partial}{\partial i} \left\{ \frac{n^2 i}{R_{m_eq}(x_g, i)} \right\} \quad (A3)$$

where, $R_{m_eq}(x_g, i)$ is an equivalent magnetic reluctance.

The equivalent magnetic reluctance is obtained from analogy of electric and magnetic circuit and is expressed as

$$R_{m_eq}(x_g, i) = \frac{(R_{11} + R_{12})(R_{21} + R_{22})}{R_{11} + R_{12} + R_{21} + R_{22}} + R_3 \quad (A4)$$

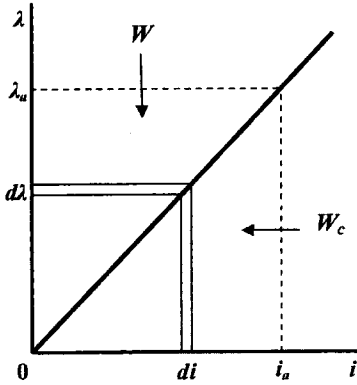


Fig. A1 Energy and co-energy stored in a magnetic field of a singly excited electromagnetic system

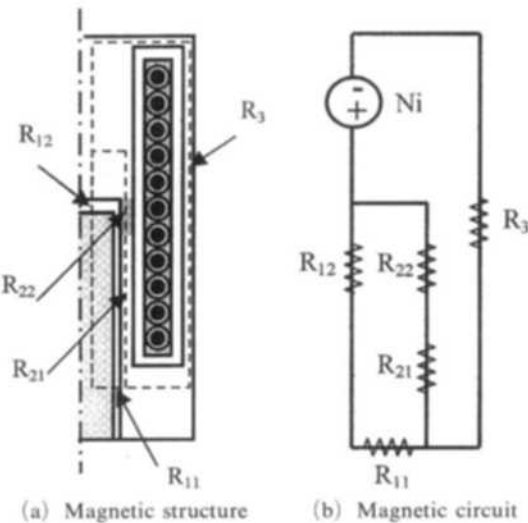


Fig. A2 Simplified magnetic model of electromagnetic control valve

where, $R_{11} = \frac{g_s}{\mu_0 \pi d_p h_b}$, $R_{12}(x) = \frac{x_g}{\mu_0 \frac{\pi}{4} d_p^2}$,

$$R_{21}(x, i) = \frac{h_{p_g} - l_{sat}(x_g, i)}{\mu_{p_g} \frac{\pi}{4} (d_{p_g}^2 - d_p^2)}$$

$$R_{22}(x, i) = \frac{l_{sat}(x_g, i)}{\mu_0 \frac{\pi}{4} (d_{p_g}^2 - d_p^2)}$$

and $R_3 = \frac{h_{cv}}{\mu_{cv} \pi t_{cv} d_{cv}}$ is a magnetic reluctance of each magnetic flux path shown in Fig. A2 (b) and g_s is a side air gap between plunger and p-guide, d_p is a diameter of plunger, h_b is a height of base, h_{p_g} is a height of p-guide, l_{sat} is a saturation length of p-guide, μ_{p_g} is a magnetic permeability of p-guide, μ_{cv} is a magnetic permeability of cover, t_{cv} is a thickness of cover, d_{cv} is a diameter of cover.

The back-emf voltage induced in a coil due to the electromagnetic flux crossing the air gap is expressed as

$$E(x_g, i) = \frac{\partial \lambda(x_g, i)}{\partial x_g} = \frac{\partial}{\partial x_g} \left\{ \frac{n^2 i}{R_{m_eq}(x_g, i)} \right\} \quad (A5)$$

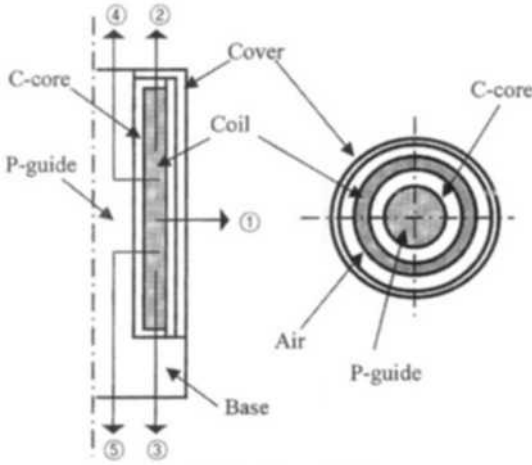
From the Eq. (A4) and (A5), inductance and back-emf is a function of design variables such as air gap length, coil diameter, p-guide thickness.

A.2

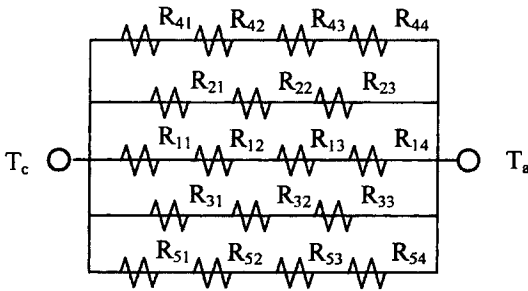
The source of heat is current that flows through the coil with resistance. The heat dissipation occurs by convection, conduction, and both of them. The heat dissipation model of the electromagnetic control valve is presented in Fig. A3. The path of heat transfer is divided by five paths as shown in Fig. A3(a), where path1 shows a heat transfer from coil to side cover, path2 is from coil to upper cover, path3 is from coil to base, path4 is from coil to upper p-guide, and path5 is from coil to lower p-guide. In heat dissipation model, temperature gradation in coil area is assumed to do not exist.

The heat generated from coil is given by

$$q_s = i^2 R \quad (A6)$$



(a) Simplified schematic diagram



(b) Electrical analog

Fig. A3 Heat dissipation model of the electromagnetic control valve

and total heat dissipated through the each heat transfer path is given by

$$q_d = \frac{\Delta T}{\sum R_{th}} = \frac{T_c - T_a}{R_{11} + R_{12} + R_{13} + R_{14}} + \frac{T_c - T_a}{R_{21} + R_{22} + R_{23}} + \frac{T_c - T_a}{R_{31} + R_{32} + R_{33}} + \frac{T_c - T_a}{R_{41} + R_{42} + R_{43}} + \frac{T_c - T_a}{R_{51} + R_{52} + R_{53}} \quad (A7)$$

where, ΔT is a temperature difference between air and coil, $\sum R_{th}$ is a total thermal resistances,

$$R_{11} = \frac{1}{2\pi r_3 L_c h}, \quad R_{12} = \frac{1}{2\pi r_4 L_c h}, \quad R_{13} = \frac{\ln(r_5/r_4)}{2\pi k_{cv} L_c},$$

$$R_{14} = \frac{1}{2\pi r_5 L_c h}, \quad R_{21} = \frac{t_{cc}}{\pi(r_3^2 - r_2^2) k_{cc}},$$

$$R_{22} = \frac{r_5 - r_4}{\pi(r_4^2 - r_1^2) k_{cv}}, \quad R_{23} = \frac{1}{\pi(r_4^2 - r_1^2) h},$$

$$R_{31} = \frac{t_{cc}}{\pi(r_3^2 - r_2^2) k_{cc}}, \quad R_{32} = \frac{h_b}{\pi(r_4^2 - r_1^2) k_b},$$

$$R_{33} = \frac{1}{\pi(r_4^2 - r_1^2) h}, \quad R_{41} = \frac{\ln(r_1/r_2)}{\pi k_{cc} L_c},$$

$$R_{42} = \frac{t_{cc} + (r_5 - r_4)}{\pi r_1^2 k_{p,g}}, \quad R_{43} = \frac{1}{\pi r_1^2 h},$$

$$R_{51} = \frac{\ln(r_1/r_2)}{\pi k_{cc} L_c}, \quad R_{52} = \frac{t_{cc} + h_b}{\pi r_1^2 k_b}, \quad R_{53} = \frac{1}{\pi r_1^2 h}$$

is a thermal resistance of the each heat transfer path shown in Fig. A3 (b) and t_{cc} is a thickness of c-core, L_c is a height of coil stack, h_b is a height of base, r_1, r_2, r_3, r_4, r_5 are radius of p-guide, c-core, coil, inner cover, and outer cover, respectively. The convection coefficient of air (h) is $4.5 \text{ W/m}^2\text{C}$ and conduction coefficient of p-guide ($k_{p,g}$) is $204 \text{ W/m}^2\text{C}$, cover (k_{cv}) and base (k_b) are $54 \text{ W/m}^2\text{C}$, air (k_a) is $0.024 \text{ W/m}^2\text{C}$, and c-core (k_{cc}) is $1.83 \text{ W/m}^2\text{C}$, respectively (Holman, 1981).

From Eq. (A6) and (A7), the temperature of coil is obtained by identifying generated heat and dissipated heat.

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