Pi Controller Design for Stable Solenoid Valve System Using the Scheduling of Control Gain

Yongho Jeon, Shinwon Lee

Abstract: ***Solenoid valves are widely used in the industrial field and require systems that include position control. The solenoid valve exhibits a characteristic that the inductance changes depending on the position of the iron core in the solenoid coil, and has a very nonlinear relationship. In the control of the nonlinear system, the control gain of the controller has the inconvenience of adjusting again according to the change of the reference position. In this work, it designed PI controller for position control of solenoid valve system with strong nonlinearity and design gain scheduler in which each gain of controller is automatically calculated as a function of position reference. When designing the gain scheduler, this system first was designed the mechanical part and the electric circuit part separately. And then, all are designed with PI control. The proposed controller has a steady - state error of less than 0.5 [%] and has almost the same control performance with respect to the positional reference input of each step.***

Index Terms: ***Gain scheduling, Nonlinear, PI control, Plunger, Solenoid valve.***

I. INTRODUCTION

The solenoid valve is a device that regulates the pressure, flow rate and direction of fluid by opening and closing the valve by supplying or cutting off current by winding a coil around the outside of the plunger, called a moving iron core. In many places in the industrial field, it is widely used from simple opening and closing operations to precise position control. [1-13]

The solenoid valve exhibits a characteristic that the inductance changes depending on the position of the iron core in the solenoid coil, and has a very nonlinear relationship. In the control of the nonlinear system, the control gain of the controller has the inconvenience of adjusting again according to the change of the reference position. To control the valve, it must be designed to linearize at the operating point for nonlinearities and to have similar response performance for multiple reference inputs.

In this study, the stability of the nonlinear solenoid valve system is determined and the appropriate control gain is designed according to the reference position in the mechanical system. Next, the control gain of the electrical system is designed by considering the control input in the mechanical system as the current reference of the electrical system, and its performance is examined.

II. GAIN SCHEDULED PI CONTROLLER

A. Position PI controller design

The mechanical equation of the mechanical part of the solenoid valve is given by the following equation (2.1).

$$\dot{v} = (aL'/(2M(x+a)^2))i^2 - (b/M)v - (K/M)x - g_r \quad (2.1)$$

$$L' = (\pi d\mu_0 aN^2)/g \quad (2.2)$$

Where x is the position of the plunger and v is the velocity of the plunger, i is the current through the coil. M is the mass of the plunger, b is the coefficient of friction between the plunger and the guide tube, a is the length of the gap, L' is the constant of the inductance, and gr is the gravitational acceleration. When the state variable is x, v, and the input is u = i in equation (2.1), the state equation is as in the equation (2.3) to the equation (2.5).

$$\dot{x} = f_1 = v \quad (2.3)$$

$$\dot{v} = f_2 = \left(aL'/(2M(x+a)^2)\right)u^2 - (b/M)v - (K/M)x - g_r \quad (2.4)$$

$$\dot{\sigma} = f_3 = e = x - r \quad (2.5)$$

In Eq. (2.5), r is the reference position and it defined the position error. In equation (2.3), the equilibrium point for the equation of state in equation (2.5) is given by the following equation (2.6).

$$\begin{bmatrix} x_{ss} \\ v_{ss} \\ u_{ss} \end{bmatrix} = \begin{bmatrix} \alpha \\ 0 \\ (a+\alpha)\sqrt{2(K\alpha + Mg_r)/aL'} \end{bmatrix} \quad (2.6)$$

The PI controller for the control input u in Eq. (2.4) is shown in the following equation (2.7).

If the state variable is in steady state and operates at the equilibrium point, linearizing the equation (2.3) to the equation (2.7) near the equilibrium point is expressed by equation (2.8) to equation (2.14).

$$\begin{bmatrix} \dot{x} \\ \dot{v} \\ \dot{\sigma} \end{bmatrix} = \begin{bmatrix} f_1(x,v,\sigma,u) \\ f_2(x,v,\sigma,u) \\ f_3(x,v,\sigma,u) \end{bmatrix}\Bigg|_{\substack{x=x_{ss}\\ v=v_{ss}\\ \sigma=\sigma_{ss}\\ u=u_{ss}}} + \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial v} & \frac{\partial f_1}{\partial \sigma} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial v} & \frac{\partial f_2}{\partial \sigma} \\ \frac{\partial f_3}{\partial x} & \frac{\partial f_3}{\partial v} & \frac{\partial f_3}{\partial \sigma} \end{bmatrix}\Bigg|_{\substack{x=x_{ss}\\ v=v_{ss}\\ \sigma=\sigma_{ss}\\ u=u_{ss}}} \begin{bmatrix} x - x_{ss} \\ v - v_{ss} \\ \sigma - \sigma_{ss} \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1}{\partial u} \\ \frac{\partial f_2}{\partial u} \\ \frac{\partial f_3}{\partial u} \end{bmatrix}\Bigg|_{\substack{x=x_{ss}\\ v=v_{ss}\\ \sigma=\sigma_{ss}\\ u=u_{ss}}} [u - uss] \quad (2.8)$$

$$\begin{bmatrix} x_{ss} \\ v_{ss} \\ u_{ss} \end{bmatrix} = \begin{bmatrix} \alpha \\ 0 \\ -k_{xi}\sigma_{ss} \end{bmatrix} \quad (2.9)$$

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Yongho Jeon Department of Aviation Maintenance Engineering Jungwon University, Republic of Korea.
Shinwon Lee,Department of Computer Engineering Republic of Korea.

$$\partial f_2/\partial x = -2(K\alpha + Mg_r)/(M(\alpha + a)) - K/M = -A \quad (2.10)$$

$$\partial f_2/\partial v = -b/M = -B \quad (2.11)$$

$$\partial f_2/\partial u = \sqrt{2aL'(K\alpha + Mg_r)}/(M(a + \alpha)) = C \quad (2.12)$$

$$\frac{\partial f_1}{\partial x} = \frac{\partial f_1}{\partial \sigma} = \frac{\partial f_2}{\partial \sigma} = \frac{\partial f_3}{\partial v} = \frac{\partial f_3}{\partial \sigma} = \frac{\partial f_1}{\partial u} = \frac{\partial f_3}{\partial u} = 0 \quad (2.13)$$

$$\frac{\partial f_1}{\partial v} = \frac{\partial f_3}{\partial x} = 1 \quad (2.14)$$

The equation (2.9) to (2.14) are substituted into the equation (2.8) and can be summarized as equation (2.15) to equation (2.17)

$$\dot{\xi}_\delta = \begin{bmatrix} 0 & 1 & 0 \\ -A - k_{xp}C & -B - k_{vp}C & -k_{xi}C \\ 1 & 0 & 0 \end{bmatrix} \xi_\delta + \begin{bmatrix} 0 \\ k_{xp}C \\ -1 \end{bmatrix} r_\delta \quad (2.15)$$

$$\begin{bmatrix} x - x_{ss} \\ v - v_{ss} \\ \sigma - \sigma_{ss} \end{bmatrix} = \xi_\delta \quad (2.16)$$

$$r - x_{ss} = r_\delta \quad (2.17)$$

The equation (2.15) is the error equation near the equilibrium point. The characteristic equation is shown in the following equation (2.18).

$$\Delta_{\text{eq. 2.15}} = s^3 + \left(B + k_{vp}C\right)s^2 + \left(A + k_{xp}C\right)s + k_{xi}C \quad (2.18)$$

The roots of Eq. (2.18) have three roots. If one real root is set to s1, then the following equation (2.19) is obtained.

$$\begin{aligned} \Delta &= (s + s_1)(s^2 + 2\zeta\omega_n s + \omega_n^2) \\ &= s^3 + (s_1 + 2\zeta\omega_n)s^2 + (2s_1\zeta\omega_n + \omega_n^2)s + s_1\omega_n^2 \end{aligned} \quad (2.19)$$

When the gain is determined by the equations (2.18) and (2.19), the following equations (2.20) to (2.22) are obtained.

$$k_{vp} = (s_1 + 2\zeta\omega_n - B)/C \quad (2.20)$$

$$k_{xp} = (2s_1\zeta\omega_n + \omega_n^2 - A)/C \quad (2.21)$$

$$k_{xi} = s_1\,\omega_n^2/C \quad (2.22)$$

If the gain of equation (2.22) is used in equation (2.20) and the output is the plunger position of equation (2.24), the output is given by the following equation (2.23).

$$\begin{aligned} y_\delta \\ = [1 \quad 0 \quad 0] \begin{bmatrix} s & -1 & 0 \\ 2s_1\zeta\omega_n + \omega_n^2 & s + s_1 + 2\zeta\omega_n & s_1\omega_n^2 \\ -1 & 0 & s \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ s_1\omega_n^2 \\ -1 \end{bmatrix} r_\delta \end{aligned} \quad (2.23)$$

$$y_\delta = [1 \quad 0 \quad 0]\xi_\delta \quad (2.24)$$

B. Current PI controller design

The circuit equation of the solenoid valve applying the Kirchhoff Voltage Law is expressed by the following equation (2.25).

$$V = Ri + \frac{d}{dt}\left(L'i\,x/(x + a)\right) \quad (2.25)$$

The resistance R in equation (2.25) is the dominant component in the coil, and the inductance of the coil is a function of the position of the plunger. The position x and velocity v of the plunger and the current i flowing through the coil are summarized in the following equation (2.26).

$$\frac{di}{dt} = \left((x + a)/(L'x)\right)\left(V - iR - iv\;a/(x + a)^2\right) \quad (2.26)$$

The V in equation (2.26) is the supply voltage source. If the control input is composed of the current reference i_r and the equation (2.7), the following equations (2.27) to (2.28) are obtained.

$$V = iR + iv\,a/(x + a)^2 + \left((L'x)/(x + a)\right)\left(k_{ip}e_i + kiieidt\right. \quad (2.27)$$

$$e_i = i_r - i \quad (2.28)$$

In Equation (2.27), kip is the proportional gain to the current error and kii is the integral gain.

III. RESULTS

The parameters of the solenoid valve used to verify the designed controller are shown in Table 1.

Table 1 The Parameter of the Solenoid valve

Parameter	N(turns)	M(kg)	b(Ns/m)	K(N/m)	R(Ω)	L'(mH)
value	200	0.3	2	2667	1	23.69

The gain-scheduled controller of the plunger is given by equation (2.27) and each gain is designed as equation (2.20) to equation (2.22). The extreme values used have the multiple root in -10 and -1. The controller for current is the same as Eq. (2.27) and designed to have -100 redundant roots of current controller.

In Figure 1, the first is the controlled state for the current state, the second is the controlled state for the position of the plunger, and the third is the result for the speed state of the plunger. The reference position is 4 mm in 3 seconds, 6 mm in 5 seconds, 8 mm in 7 seconds and 10 mm in 9 seconds. It can be seen that the position error is accurately controlled within 0.5% in steady state. Also, it can be seen that the overshoot and vibration of the transient state are almost the same at the time when the reference position changes, so that the scheduled gain works well.

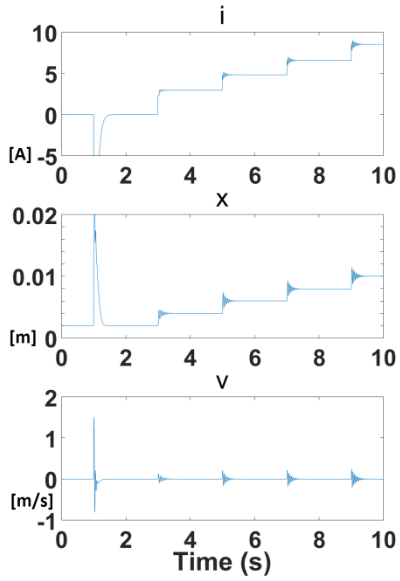

Fig. 1 Output State of the Gain-Scheduled Controller

Figure 2 shows the result when a constant disturbance is applied to the plunger. As a result of constant disturbance 2 [Nm] operating at 4 seconds and removed again at 6 seconds, the current state of the first picture increased from 2.96 [A] to 3.14 [A] in 4 seconds, A steady-state error occurred at 4 [mm] to 3.6 [mm]. The controller designed to operate with disturbance has a position error of 40 [%] in steady state with respect to disturbance.

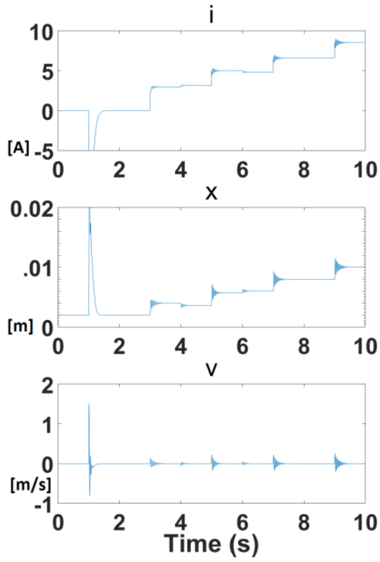

Fig. 2 applied disturbance 2[Nm]

IV. CONCLUSION

The solenoid valve system has a strong nonlinear characteristic and is a controller designed by linearizing at the equilibrium point. In this work, it designed PI controller for position control of solenoid valve system with strong nonlinearity and design gain scheduler in which each gain of controller is automatically calculated as a function of position reference. When designing the gain scheduler, this system first was designed the mechanical part and the electric circuit part separately. And then, all are designed with PI control. The proposed controller has a steady state error of less than 0.5 [%] and has almost the same control performance with respect to the positional reference input of each step. There are overshoot and oscillation characteristics in the transient state. It is designed by separating the position controller and the current controller, but the poles of the two controllers are not completely separated and affecting. And if you design without separating the position and current controller, it is a case in which the highest order of the entire system has a fourth order, which is too complicated in design. And as a result of application of constant disturbance, the reason for the position error is that the designed controller does not consider the influence of the disturbance. A future controller design considering the effect of disturbance is required.

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