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PI Controller Design Using Luenberger's Observer

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Abstract: For precise position control of solenoid valves with strong non-linear characteristics it is essential to respond to load fluctuations including non-linear terms. We study the method of estimating the state of disturbance by considering load variation and non-linear term as disturbance and the method of applying it to controller. By constructing the Luenberger's observer with the disturbance state, the state of the observer is included in the control input to perform feedback linearization and the PI controller can be configured to achieve precise position control and this system obtains the robustness to adapt to the load variation. As a result, the robustness of maintaining the target position by the adaptation of the constant load of 5 [N] with the position error of the steady state within 0.1% was obtained.

Key words: Luenberger's observer, PI controller, non-linear, solenoid, disturbance, configured

INTRODUCTION

The solenoid valve is a device that adjusts the pressure, flow and direction of the fluid using the linear movement of the movable iron core. It is usefully used where a driving speed is short, a large force is not required and a high-speed response speed is required. The precise position control of the solenoid valve is very important in the semiconductor process in which accurate fluid flow is required. Generally using low cost ON/OFF solenoid valves are not suitable for precise position control due to the non-linear characteristics of the system and the position sensor separately (Lunge *et al*., 2013; Kajima and Kawamura, 1995; Rahman *et al*., 1995, 1996; Malaguti and Pregnolato, 2002; Obata *et al*., 2014; Franklin and Powell, 1994; Utkin, 1977; Cheung *et al*., 1993; Szente and Vad, 2001; Cheung, 1993).

In this study, a plunger (movable iron core) of solenoid valve for ON/OFF is implemented to enable precise position control without attaching a position sensor. The plunger's mathematical model must be accurate first to achieve precise position control without sensor attachment. And the plunger is linearly moved by the magnetic field induced by the current flowing in the coil wound around the plunger. The inductance is a parameter including a position variable due to the change of the size of the gap depending on the position of the plunger and the induced electromotive force generated in the electric circuit is a value of the rate of change of the magnetic flux interlinkage with respect to time. It is a strong non-linear system with a state variable of displacement in the electric equation. In addition, the fluid to be controlled such as the flow rate or the pressure, acts as a disturbance to the plunger and it is necessary to actively respond to the disturbance in order to control the mechanical force on the position of the plunger. It is a good idea to design a state observer that includes disturbances that adequately contain the limits of the mathematical model above and that can design an observer for disturbances. The design of the disturbance observer using the Luenberger's observer allows precise position control even with load variation and parameter error and it is possible to perform the sensor less control of the position by including the estimation of the position state by the current state measurement.

In this study, the disturbance observer is designed based on the assumption that the load is a constant for a certain time interval and all the disturbance including the parameter error of the inductance is defined as a constant disturbance. And it shows the performance of the steady state error and settling time through the position control of the plunger and shows robust performance against disturbance that maintains position control accuracy even for load fluctuation.

MATERIALS AND METHODS

Solenoid dynamic model: The plunger, made of ferromagnetic material has a structure of linear motion in the guide tube of the cylindrical steel material. A spring is present between one end of the plunger and the cylindrical guide tube and remains in the initial position of

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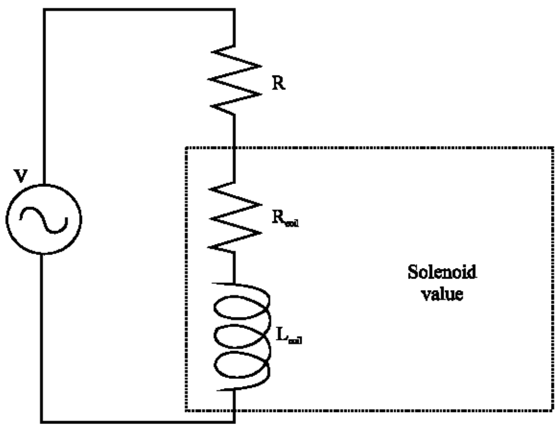

Fig. 1: A Simple electric circuit of solenoid valve

the spring in the absence of an electrical force. When the electric energy is supplied, the plunger moves upward due to the magnetic field induced thereby and spring is compressing and the plunger stops moving in a state where the spring is restored and the magnetic force is balanced.

Solenoid mechanical model (Lunge *et al.*, 2013): When the power supply for moving the plunger is V, a simple electric circuit is shown in Fig. 1. The resistance R is the resistance value at the power supply and R_{coil} is the resistance of the driving coil. And the inductance L_{coil} is the inductance of the coil and has a non-linear property depending on the distance of the plunger vertical motion.

The inductance is a function that takes the distance x of the plunger movement as a variable and is expressed by the following Eq. 1:

$$L(x) = \frac{\pi d\mu_0 aN^2}{g}\left(\frac{x}{x+a}\right) = L'\left(\frac{x}{x+a}\right) \quad (1)$$

The Kirchhoff Voltage Law (Kirchhoff Voltage Law) is applied in Fig. 2 and the circuit equation is shown in the following Eq. 2:

$$V = Ri+R_{coil}\, i+\frac{d}{dt}\big(L(x)i\big) = Ri+R_{coil}i+ i\frac{dL(x)}{dx}\frac{dx}{dt}+L(x)\frac{di}{dx} \quad (2)$$

The resistance R of Eq. 2 is smaller than R_{coil}, the second term from the end is the value corresponding to the back EMF and the last equation is the voltage of the inductor caused by the change of the current supplied to drive.

The total amount of the flux linkage generated by the current of the power source is the total supplied energy and if it is differentiated according to the distance variable x, the magnetic force $F_{magnetic}$ can be obtained (Eq. 3):

$$F_{magnetic} = \frac{\partial}{\partial x}\big(L(x)I^2\big) = \frac{1^2}{2}\frac{aL'}{(x+a)^2} \quad (3)$$

Constructing a mechanical dynamics equation for all the forces acting on the plunger is shown in the following Eq. 4:

$$M\frac{d^2x}{dt^2} = F_{magnetic}-B\frac{dx}{dt}-Kx-Mg_r \quad (4)$$

Where:

M = The mass of the plunger
B = The coefficient of viscous friction between the guide tube and the plunger
K = The stiffness due to the displacement
g_r = The gravitational acceleration

Using Eq. 1-4 when the state equation is derived it is the following Eq. 5-7:

$$\dot{x} = v \quad (5)$$

$$\dot{v} = \Big(aL'/\,2M\big((x+a)^2\big)\Big)i^2-(B/M)v(K/M)x-g_r \quad (6)$$

$$\dot{i} = \big((x+a)/(L'x)\big)V-\big((R+R_{coil})(x+a)/(L'x)\big)i-\big(a/(x(x+a))\big)iv \quad (7)$$

Where:

x = The displacement of the plunger
v = The speed of movement of the plunger
i = The current through the plunger coil
V = The supply voltage source

Equation 6 and 7 are non-linear equation.

Observer design: This system is constructed by taking the position, speed and current of the plunger as state variables, taking $u = i^2$ as an input variable of mechanical equation and using the voltage supplied to both ends of the plunger coil as an input V of the electric (Eq. 8-12):

$$\begin{pmatrix}\dot{X}\\ \dot{V}\\ \dot{f}\\ \dot{i}\\ \dot{f}_i\end{pmatrix} = \begin{pmatrix}0&1&0&0&0\\0&0&1&0&0\\0&0&0&0&0\\0&0&0&0&1\\0&0&0&0&0\end{pmatrix}\begin{pmatrix}x\\ v\\ f\\ i\\ f_i\end{pmatrix}+\begin{pmatrix}0&0\\g(x)&0\\0&0\\0&g_i(x)\\0&0\end{pmatrix}\begin{pmatrix}u\\ v\end{pmatrix} \quad (8)$$

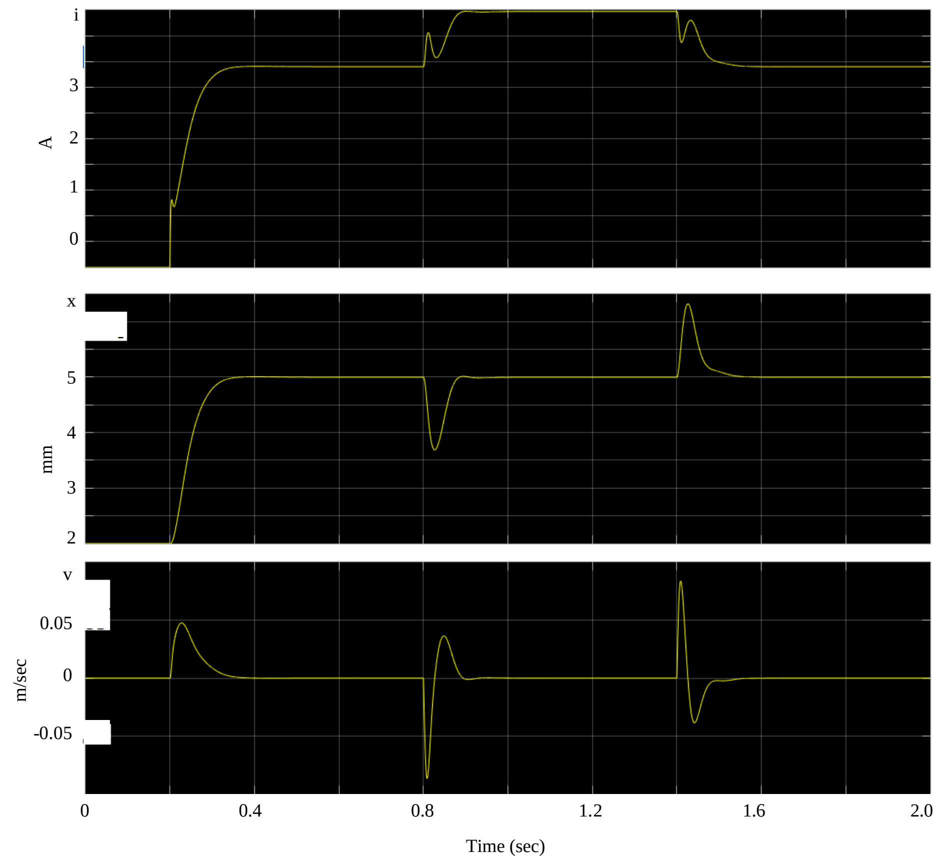

Fig. 2: The control result at 5 N load change

$$g(x) = aL'/\left(2M(x+a)^2\right) \tag{9}$$

$$f(x, v, u) = \Delta\left(aL'/2M(x+a)^2\right)u-(B/M)v-(k/M)x-g_r \tag{10}$$

$$g_i(X) = \left((x+a)/(L'x)\right) \tag{11}$$

$$f(x, v, i) = \Delta\left((x+a)/(L'x)\right)V-\left((R+R_{coil})(x+a)/(L'x)\right)i-\left(a/\left(x(x+a)\right)\right)iv \tag{12}$$

Equation 9-11 are terms that are multiplied by the mechanical and electrical inputs. Equation 10 and 11 are the disturbance formulas including the input error have constant values for a certain period of time. These equations express two state equations in a matrix.

With the state Eq. 8-12, we design a state observer with non-linearities and load variations using the Luenberger's observer (Eq. 13 and 14):

$$\begin{pmatrix} \dot{\hat{x}} \\ \dot{\hat{v}} \\ \dot{\hat{f}} \\ \dot{\hat{i}} \\ \dot{\hat{f}}_i \end{pmatrix} = \begin{pmatrix} 0&1&0&0&0 \\ 0&0&1&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&1 \\ 0&0&0&0&0 \end{pmatrix} \begin{pmatrix} \hat{x} \\ \hat{v} \\ \hat{f} \\ \hat{i} \\ \hat{f}_i \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ g(x) & 0 \\ 0 & 0 \\ 0 & g_i(x) \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} + \begin{pmatrix} I_1 & 0 \\ I_2 & 0 \\ I_3 & 0 \\ 0 & m_1 \\ 0 & m_2 \end{pmatrix} \begin{pmatrix} y-\hat{y} \\ y_i-\hat{y}_i \end{pmatrix} \tag{13}$$

$$\hat{y} = (1\ \ 0\ \ 0)\left(\hat{x}\ \ \hat{v}\ \ \hat{f}\right)^T \tag{14}$$

$$\hat{y}_i = (1\ \ 0\ \ 0)\left(\hat{i}\ \ \hat{f}_i\right)^T \tag{15}$$

I_1, I_2, I_3, m_1 and m_2 of Eq. 14 and 15 are the gains of the observer, the output of the mechanical equation is $y = x$ and the output of the electrical equation is $y_i = i$. The error equation can be derived using the state Eq. 8-12 and using the state estimation Eq. 13-15 (Eq. 16):

$$\begin{pmatrix} \dot{x}-\dot{\hat{x}} \\ \dot{v}-\dot{\hat{v}} \\ \dot{f}-\dot{\hat{f}} \\ \dot{i}-\dot{\hat{i}} \\ \dot{f}_i-\dot{\hat{f}}_i \end{pmatrix} = \begin{pmatrix} -I_1 & 1 & 0 & 0 & 0 \\ -I_1 & 0 & 1 & 0 & 0 \\ -I_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -m_1 & 1 \\ 0 & 0 & 0 & -m_2 & 0 \end{pmatrix} \begin{pmatrix} x-\hat{x} \\ v-\hat{v} \\ f-\hat{f} \\ i-\hat{i} \\ f_i-\hat{f}_i \end{pmatrix} \quad (16)$$

Equation 17 gives the characteristic equation of Eq. 16 for setting the observation gain of whole system:

$$\Delta(S) = \left(S^3+I^1S^2+I_2S+I_3\right)\left(S^2+m_1S+m\right) \quad (17)$$

Equation 17 is the total fifth-order equation obtained by multiplying the cubic and quadratic equations in the s-domain. The root of the cubic equation is the root of the mechanical error equation which places all the roots of the quadratic equation on the left hand side. When the gain is determined in consideration of the overall response characteristic and the range of the input values of the mechanical equations and the electrical equations, the estimation error converges to zero asymptotically.

PI controller design: The controller is widely used in the industrial field and constitutes using a general proportional integral controller. The configuration of the controller is divided into a mechanical part and an electrical part. The observer design is divided into electrical part and mechanical part which is a way to overcome the problem of difficulty in setting the gain due to the increase in the order of the system.

To control the position of the plunger, the PI controller of the mechanical part is designed according to the following Eq. 18:

$$u = \frac{1}{g(x)}\left(u_m-\hat{f}\right) \quad (18)$$

$$u_m = K_p\left(r-\hat{x}_1\right)+k_i\int\left(r-\hat{x}_1\right)dt \quad (19)$$

Equation 18 and 19 is a controller using the state of disturbance $\hat{f}$ and state estimation of Eq. 13. Where r is the reference position K_p is the proportional control gain and K_i is the integral control gain (Table 1).

The control input u composed of Eq. 18 is set to i^2_{ref} and obtains the reference current for following the electrical system equation. If the PI controller of the electric part is designed by using this it is the following Eq. 20 and 21:

Table 1: The gain of the controller

Gain	Values
K_p	14 K
K_i	100 M
K_{ip}	140
K_{ii}	10 K

$$v = \frac{1}{g_i(x)}\left(V_i-\hat{f}_i\right) \quad (20)$$

$$V_i = K_{ip}\left(i_{ref}-\hat{i}\right)+k_{ii}\int\left(i_{ref}-\hat{i}\right)dt \quad (21)$$

Equation 20 and 21 is the result of designing the controller using the state estimated in Eq. 13.

RESULTS AND DISCUSSION

The gain of the error observer of the designed Eq. 13 is I_1 = 3 K, I_2 = 9 M, I_3 = 1 G, m_1 = 200 and m_2 = 10 K. The gain of the controller is shown in Table 1.

Figure 2 shows that each state is controlled. The first figure is the position state, the second is the speed state and the third is the current state. The gain of the controller is shown in Table 1.

It travels from the initial position 2 mm at time 0.2 sec to the target position 5 mm. It is close to critical braking and the target value 99% reaching 0.138 sec. When the constant load of 5 N is applied at a time of 0.8 sec, the plunger is displayed in the undershoot moving forward about 2.3 mm and it is recovered within about 0.1 sec.

In addition, when the load is removed at 1.4 sec, overshoot occurs and it is recovered within about 0.15 sec. The second shows that the control is performed well with the speed state and the last current state.

As a result, the disturbance estimated by the observer is actively reflected to the controller to remove the disturbance and the steady state error is reflected to the load variation within 0.1% to be robust to the disturbance.

CONCLUSION

The observation of the state is essential for precise control and observation of the disturbance is required. However, since, the disturbance is not easy to observe it is possible to apply the estimation method using the state observer and configure the general PI controller to check its performance.

In this study, it is confirmed that the error of steady state is <1% by setting proper gain of PI controller based on the state estimation for the load variation.

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