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Observer Design Using Luenberger's Observer

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Abstract: Commonly used solenoid valves are mainly used for industrial equipment and appliances where simple ON/OFF operation is possible. This is because the structure of the solenoid valve is simple and the production cost is low. It is possible to simply use the alternating method of applying the drive rated voltage or turning off the power. This study designs a controller for precise position control and a Luenberger's observer for unobserved states in the use of solenoids commonly used in the industrial field. In designing an observer an observer with a disturbance state including a non-linear term and a constant load is designed and an appropriate gain is set. As a result, the position error was within 0.1% within about 0.1 sec of the steady state, the state estimation for the disturbance could be possible and it could be used in the position controller.

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

INTRODUCTION

A solenoid is an electromagnet which is made to be able to convert electric energy into mechanical linear motion by allowing a current to flow by winding a coil around a moving iron core. Commonly used solenoid valves are mainly used for industrial equipment and appliances where simple ON/OFF operation is possible. This is because the structure of the solenoid valve is simple and the production cost is low. It is possible to simply use the alternating method of applying the drive rated voltage or turning off the power (Lunge *et al*., 2013; Rahman *et al*., 1995a, b, 1996; Kajima and Kawamura, 1995; Malaguti and Pregnolato, 2002; Obata *et al*., 2014; Franklin and Powell, 1994; Utkin, 1977; Cheung *et al*., 1993; Szente and Vad, 2001; Cheung, 1993).

However, there is a disadvantage in that power consumption is inefficient and durability is impaired due to frequent noise and frequent shocks. When the driving displacement is short and precise position control of the plunger is required, a method of precisely controlling the position of the plunger using a motor is used.

Including the motor and the position sensor for position control, the structure of the valve is complicated and it costs a lot in manufacturing. In order to control the position, a state observer must be constructed. The solenoid valve has a motion equation of a third-order differential equation with a strong non-linearity with respect to the positional state.

A non-linear state observer based on a general Luenberger's observer is designed and used for position control by estimating the state variables. In addition, the load variation and the error of the parameter have an important influence on the precise position control. Even if it is assumed the constant disturbance that includes the load is assumed to be a constant for a certain period of time and the error of the parameter in practice because the load fluctuation occurs in real time and the disturbance is not constant, it is defined as perturbation. And by incorporating its influence into the observer, it is possible to set the observation gain, there by minimizing the observation error and improving the performance of the observer and showing a precise position.

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 (Fig. 1). A spring is present between one end of the plunger and the cylindrical guide tube and remains in the initial position of 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 there by and spring is compressing and the plunger stops moving in a state where the spring is restored and the magnetic force is balanced.

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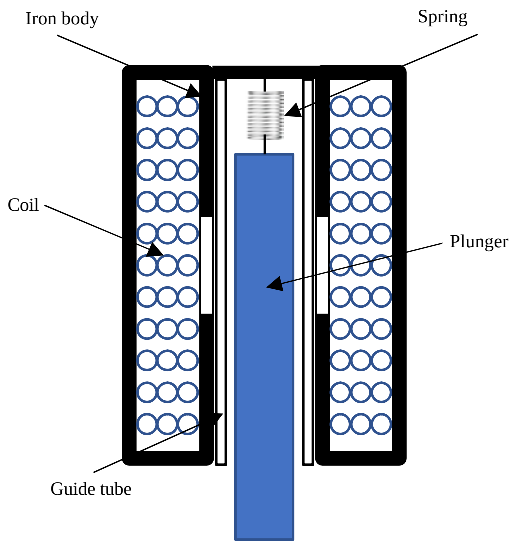

Fig. 1: Mechanical structure of solenoid value

The magnet flux induced to move the plunger is proportional to the number of turns of the coil wound on the guide of the cylindrical steel material and the amount of current supplied. In addition when the plunger moves upward, the air gap becomes smaller overall, the reluctance decreases and the inductance increases.

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. 2. 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:

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

The Kirchhoff voltage law is applied in Fig. 1 and the circuit equation is shown in the following Eq. 2:

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

The resistance R of Eq. 2 is smaller than R_{coil}, the second term from the end is the value corresponding to

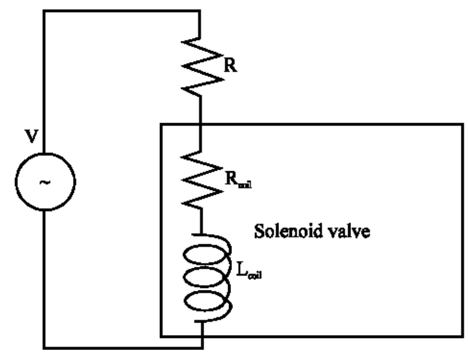

Fig. 2: A simple electric circuit of solenoid valve

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. This is the following Eq. 3:

$$F_{magnetic} = \frac{\partial}{\partial x}\left(L(x)i^2\right) = \frac{i^2}{2}\frac{aL'}{(x+a)^2} \quad (3)$$

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:

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

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

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

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

Observer design: The position and speed of the plunger are set as state variables, $U = i^2$ is an input variable, Eq. 5-6 can be expressed by the mechanical state equation as the following Eq. 8-13:

$$\dot{x} = v \tag{8}$$

$$\dot{v} = g(x)u+f(x,v,u) \tag{9}$$

$$\dot{f} = 0 \tag{10}$$

$$g(x) = aL'/\left(2M(x+a)^2\right) \tag{12}$$

$$f(x,v,u) = \Delta\left(aL'/2M(x+a)^2\right)u-(B/M)v-(K/M)x-g_r \tag{13}$$

Equation 12 is the term multiplied by the input, including the error. Equation 13 is disturbance and is a constant value for the interval as expressed by Eq. 10.

If we design the Luenberger's observer according to the state equation of Eq. 8-10, it is the following Eq. 14-15:

$$\begin{pmatrix}\dot{\hat{x}}\\ \dot{\hat{v}}\\ \dot{\hat{f}}\end{pmatrix} = \begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\hat{x}\\ \hat{v}\\ \hat{f}\end{pmatrix}+\begin{pmatrix}0\\ g(x)\\ 0\end{pmatrix}u+\begin{pmatrix}l_1\\ l_2\\ l_3\end{pmatrix}(y-\hat{y}) \tag{14}$$

$$\hat{y} = (1 \quad 0 \quad 0)\left(\hat{x} \quad \hat{v} \quad \hat{f}\right)^T \tag{15}$$

I_1, I_2 and I_3 of Eq. 14 are the gains of the observer and the output is y = x. Deriving the error equation using the observer of Eq. 15 and the state equation of Eq. 8-10 is given by the following Eq. 16:

$$\begin{pmatrix}\dot{x}-\dot{\hat{x}}\\ \dot{v}-\dot{\hat{v}}\\ \dot{f}-\dot{\hat{f}}\end{pmatrix} = \begin{pmatrix}-l_1 & 1 & 0\\ -l_2 & 0 & 1\\ -l_3 & 0 & 0\end{pmatrix}\begin{pmatrix}x-\hat{x}\\ v-\hat{v}\\ f-\hat{f}\end{pmatrix} \tag{16}$$

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

$$\Delta_m(s) = s^3+l_1s^2+l_2s+l_3 \tag{17}$$

Place the root of Eq. 17, so that, it has the triplet pole on the left hand side. That is, the observer gain is set, so that, the error Eq. 17 converges to zero.

Next with Eq. 7 and the current i, if the electric current state equation are constructed, Eq. 18-20 are as follows:

$$\dot{i} = g_i(x)V+f_i(x,v,i) \tag{18}$$

$$g_i(x) = \left((x+a)/(L'x)\right) \tag{19}$$

$$f(x,v,i)_i = \Delta\left(\frac{(x+a)}{(L'x)}\right)V-\left(\frac{(R+R_{coil})(x+a)}{(L'x)}\right)i-\left(\frac{a}{(x(x+a))}\right)iv \tag{20}$$

If the observer of the electrical system is constructed based on the state including the disturbance of Eq. 18-20 it is the following Eq. 21-22:

$$\begin{pmatrix}\dot{\hat{i}}\\ \dot{\hat{f}}_i\end{pmatrix} = \begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}\begin{pmatrix}\hat{i}\\ \hat{f}_i\end{pmatrix}+\begin{pmatrix}g_i(x)\\ 0\end{pmatrix}V+\begin{pmatrix}m_1\\ m_2\end{pmatrix}(y_i-\hat{y}_i) \tag{21}$$

$$\hat{y}_i = (1 \quad 0)\left(\hat{i} \quad \hat{f}_i\right)^T \tag{22}$$

When the output is the current flowing through the coil, Eq. 22 is the observation equation for the output. Equation 18-21 are used in the electrical system to determine the gain m_1, m_2 of the observer and the error equation is obtained by the following Eq. 23:

$$\begin{pmatrix}\dot{i}-\dot{\hat{i}}\\ \dot{f}_i-\dot{\hat{f}}_i\end{pmatrix} = \begin{pmatrix}-m_1 & 1\\ -m_2 & 0\end{pmatrix}\begin{pmatrix}i-\hat{i}\\ f_i-\hat{f}_i\end{pmatrix} \tag{23}$$

The characteristic equation of the error equation of Eq. 23 is shown in the following Eq. 24:

$$\Delta_i(s) = s^2+m_1s+m_2 \tag{24}$$

If the observer gains m_1, m_2 are designed, so that, the roots of Eq. 24 are located on the left side and have a midpoint, the observation error converges to zero asymptotically.

RESULTS AND DISCUSSION

Figure 3 shows the error between the estimated value and the actual value of the state observer. The first figure is the error of the position state, the second is the error of the velocity state and the third is the error of the current state. The gain of the error observer is shown in Table 1.

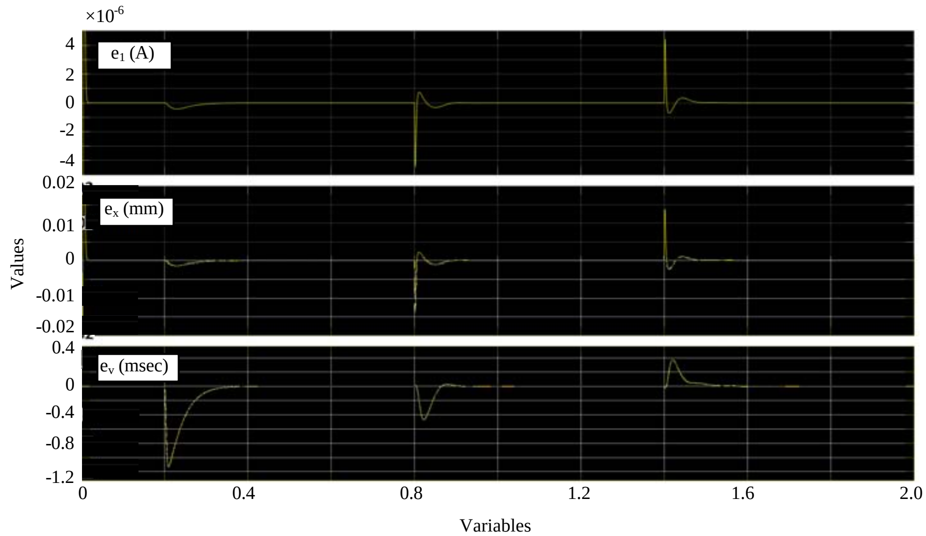

Fig. 3: Error of state variable at state estimation

Table 1: The gain of the observer

Gain	Values
l_1	3 K
l_2	9 M
l_3	1 G
m_1	200
m_2	10 K

This is the estimation error. The initial position is 2 mm and the position is controlled to move to 5 mm in 0.2 sec and a constant load of 5 N is applied to the load in 0.8 sec and the load is removed in 1.4 sec. Estimation error when loading is applied at 1.4 sec after 5 N to be. Each steady state error has a value within 1%.

CONCLUSION

The observation of each state is required for precise position control of a solenoid valve system with non-linear state equations. In this study, we designed a state observer and estimated the speed and the disturbance of the plunger. As a result, it can be confirmed that the estimation error of each position, speed, current and load condition can be made within 1% and it can be used for precise position control.

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REFERENCES

Cheung, N.C., 1993. Simulations and experimental studies towards the development of a proportional solenoid. Aust. Univ. Power Eng., 2: 582-587.

Cheung, N.C., K.W. Lim and M.F. Rahman, 1993. Modelling a linear and limited travel solenoid. Proceedings of the International Conference on Industrial Electronics, Control and Instrumentation (IECON'93), November 15-19, 1993, IEEE, Maui, Hawaii, USA., pp: 1567-1572.

Franklin, G.F. and J.D. Powell, 1994. Feedback Control of Dynamic Systems. 3rd Edn., Addison Wesley, Boston, Massachusetts, Pages: 196.

Kajima, T. and Y. Kawamura, 1995. Development of a high-speed solenoid valve: Investigation of solenoids. IEEE. Trans. Ind. Electron., 42: 1-8.

Lunge, S.P., S. Kurode and B. Chhibber, 2013. Proportional actuator from on off solenoid valve using sliding modes. Proceedings of the 1st International and 16th National Conference on Machines and Mechanisms (iNaCoMM'13), December 18-20, 2013, Indian Institute of Technology Roorkee, Roorkee, India, pp: 1020-1027.

Malaguti, F. and E. Pregnolato, 2002. Proportional control of on/off solenoid operated hydraulic valve by nonlinear robust controller. Proceedings of the IEEE International Symposium on Industrial Electronics Vol. 2, July 8-11, 2002, IEEE, L'Aquila, Italy, pp: 415-419.

Obata, S., T. Haneyoshi and Y. Saito, 2014. New linear solenoid actuator for humanoid robot. Proceedings of the 10th France-Japan and 8th Europe-Asia Conference on Mecatronics (MECATRONICS'14), November 27-29, 2014, IEEE, Tokyo, Japan, ISBN:978-1-4799-5718-7, pp: 367-370.

Rahman, M.F., N.C. Cheung and K.W. Lim, 1995. A sensorless position estimator for a nonlinear solenoid actuator. Proceedings of the 1995 IEEE IECON 21st International Conference on Industrial Electronics, Control and Instrumentation Vol. 2, November 6-10, 1995, IEEE, Orlando, Florida, USA., pp: 1208-1213.

Rahman, M.F., N.C. Cheung and K.W. Lim, 1995. Position estimation in solenoid actuators. Proceedings of the Thirtieth IAS Annual Meeting IAS '95 and IEEE Record of 1995 Joint Conference on the Industry Applications Vol. 1, October 8-12, 1995, IEEE, Orlando, Florida, USA., pp: 476-483.

Rahman, M.F., N.C. Cheung and K.W. Lim, 1996. Position estimation in solenoid actuators. IEEE. Trans. Ind. Appl., 32: 552-559.

Szente, V. and J. Vad, 2001. Computational and experimental investigation on solenoid valve dynamics. Proceedings IEEE/ASME International Conference on Advanced Intelligent Mechatronics Vol. 1, July 8-12, 2001, IEEE, Como, Italy, pp: 618-623.

Utkin, V.I., 1977. Variable structure systems using sliding mode. IEEE Trans. Autom. Control, 22: 212-222.