LINEARIZATION OF FORCE/STROKE CHARACTERISTIC OF SWITCHING SOLENOID USING FUZZY-LOGIC-CONTROLLER

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ABSTRACT

In this paper, the static force/stroke characteristic of switching solenoid is linearized by using the traditional PI-controller as well as the fuzzy-logic-controller. The major aim is to develop a proportional switching solenoid having the advantage of lower cost as compared with a usual proportional solenoid. Besides, two different methods to implement the linearization are adopted. One is the employment of a force sensor to generate the actual feedback force signal, and the other is the utilization of the numerically estimated pseudo-force as the feedback signal. Experimental results prove that the nonlinear fuzzy-logic-controller is superior to the conventional linear PI-controller concerning the compensation of the high nonlinearity near the end-position of the plunger.

KEY WORDS

Linearization, Switching Solenoid, Proportional Solenoid

NOMENCLATURE

- B_i : the centroid of the consequent fuzzy subset of the i th rule.
- $e(k)$: force error signal
- $u(k)$: output actuating signal of the fuzzy controller
- W_i : the degree of firing of the i th rule
- y : output of the fuzzy controller
- $\Delta e(k)$: error signal change
- $\Delta u(k)$: actuating signal change

INTRODUCTION

Among different fluidtechnic electro-mechanical transducers, the switching solenoid is perhaps the most frequently utilized one which can be found in many fluidtechnic applications, like the valves, pumps, machine tools, and many others. The static force/stroke characteristic of a switching solenoid, however, is quite nonlinear as compared with a usual proportional solenoid. Therefore, the major aim of this paper is to linearize the nonlinear force/stroke relation and develop a proportional switching solenoid. Some comparisons between switching

solenoid and proportional solenoid are shown in Fig. 1. It can be observed that the two kinds of solenoids have quite different force/stroke characteristics, though they possess almost the same structure. The main difference, however, is the shape of the built-in non-magnetic ring in the solenoids. Previous papers [5,6] concerning the linearization of the force/stroke curve of switching solenoid can be found in the 90's. However, only the PI-controller was employed in these reports. The results of the linearization were also not fully satisfactory especially as the plunger of the switching solenoid approaches its end-position. This is chiefly because of the highly nonlinear force/stroke relation near the plunger's end-position. In this paper, therefore, the nonlinear fuzzy-logic-controller is introduced. To linearize the force/stroke characteristic, closed-loop feedback control technique is applied. Peter Tappe (1998) presented two different methods to implement the linearization. First, a force sensor is employed to generate the actual feedback force signal. And second, instead of the expensive force sensor, the numerically estimated pseudo-force is utilized as the feedback signal. In this paper, these two different methods are both discussed.

Figure 1 Some comparisons between switching solenoid and proportional solenoid

EXPERIMENTAL DEVICE

To evaluate the static performance of the switching solenoid, an experimental test device is developed as shown in Fig. 2. To control the position of the plunger, an open-loop controlled micro-stepping motor is used. The angle and speed of rotation of the micro-stepping motor are determined directly by the number of pulse and the frequency of the generated

pulse signal sent to the driver, respectively. Moreover, the direction of rotation can be easily controlled by sending a Hi- (5V) or Lo- (0V) signal to one input port of the driver. To measure the stroke and the output force of the plunger, a position sensor (LVDT) and a load cell are constructed in the test device. This test device is also equipped with a current transformer (CT), which can be used to measure the coil current. Finally, the control of the unit as well as the acquisition and processing of data are all integrated in a PC-based controller.

Figure 2 Layout of the test device

EXPERIMENTAL RESULTS BY SENSING THE FORCE

In this section, the force signal is measured by a load cell and directly fed back to the closed-loop system. Apart from the traditional PI controller, the nonlinear fuzzy-logic-controller is also applied to the system for the purpose of comparisons. Now, we start with the basic measurement of the characteristics of a chosen switching solenoid. Figure 3 indicates the experimental results of the nonlinear force/stroke relation of the tested solenoid as a function of coil current varying from 0.1 ampere to 0.45 ampere. As shown in Fig. 3, the highly nonlinear, almost vertical force/stroke curves near the end-position (i.e. near 0 mm) are noticeable. In addition, the stroke from 0 mm to 2 mm is the ideal operating range for linearization since the force corresponding to stroke greater than 2 mm decays very quickly and is not suitable for the linearization. The block diagram of the control system is shown in Fig. 4.

Figure 3 Experimental nonlinear force/stroke relation

Figure 4 Block diagram of the control system

The optimal gains for the PI-controller can be determined by Ziegler-Nichols method [2] and are found to be $K_p=0.01$ and $K_i=0.17$ respectively. The corresponding experimental results for three different force settings, which are 15N, 20N and 25N respectively, are shown in Fig. 5. It can be seen that the results after the force linearization are remarkably oscillatory near the end-position of the plunger. In the following, the nonlinear fuzzy-logic-controller is applied to overcome this oscillation.

Unlike the conventional controller, there are three procedures involved in the implementation of a fuzzy-logic-controller, fuzzification of the input, fuzzy inference based on the knowledge and the defuzzification of the rule-based control signal.

Figure 5 Experimental results using the PI-controller

(a) Fuzzification

The two input signals to the fuzzy controller are the force error signal, $e(k)$, and its change signal, $\Delta e(k)$.

$$e(k) = F_d - F_m, \quad (1)$$

$$\Delta e(k) = e(k) - e(k-1). \quad (2)$$

Fig. 6 shows the fuzzy membership function for the two input signals to determine the degree of input.

(b) Inference

The inference process consists of a set of rules driven by the linguistic values of the error and the error change signal. Table 1 shows the definition of the rules.

Figure 6 Fuzzy membership function for two input signals

Table 1 Definition of the control rules

		$e(k)$						
		NB	NM	NS	ZE	PS	PM	PB
$\Delta e(k)$	PB	ZE	PS	PM	PB	NB	NM	NS
	PM	NS	ZE	PS	PM	PB	NB	NM
	PS	NM	NS	ZE	PS	PM	PB	NB
	ZE	NB	NM	NS	ZE	PS	PM	PB
	NS	PB	NB	NM	NS	ZE	PS	PM
	NM	PM	PB	NB	NM	NS	ZE	PS
	NB	PS	PM	PB	NB	NM	NS	ZE

(c) Defuzzification

The defuzzification is to transform control signal into exact control output. In the defuzzification, the method of center of gravity is used.

$$y = \frac{\sum_{i=1}^n W_i B_i}{\sum_{i=1}^n W_i}, \quad (3)$$

where y : output of the fuzzy controller,
 W_i : the degree of firing of the i th rule,
 B_i : the centroid of the consequent fuzzy subset of the i th rule.
The output actuating signal of the fuzzy controller, $u(k)$, is defined as

$$u(k) = u(k-1) + \Delta u(k). \quad (4)$$

Figures 7-9 show the output membership functions of the actuating signal change, $\Delta u(k)$, for the three different force settings. Using the fuzzy-logic-controller shows the corresponding experimental results of linearization in Fig. 10. As compared to Fig. 5, it is observable that the force oscillation near the end-position is greatly reduced. Therefore, a longer linear working stroke is available.

Figure 7 Output membership function for the actuating signal change (15 N)

Figure 8 Output membership function for the actuating signal change (20 N)

Figure 9 Output membership function for the actuating signal change (25 N)

Figure 10 Experimental results of linearization using the fuzzy-logic-controller

EXPERIMENTAL RESULTS BY PSEUDO-FORCE ESTIMATION

In this section, the pseudo-force feedback signal is numerically generated to minimize the cost of implementation. To do this, a look-up table is experimentally established, which consists of three parameters, the stroke, the output force of the plunger and the coil current. Since the stroke of the plunger and the coil current are easily measured and usually known, the output pseudo-force can be numerically estimated by looking up the table. Fig.11 shows graphically the experimental results of the relation between the three parameters.

Let the pseudo-force, F_p , is a function of the plunger stroke, x , and the current signal, i , thus

$$F_p(x, i) = A(x) \times i + B(x). \quad (5)$$

From the experimental results shown in Fig. 11, Table 2 can be established. By curve-fitting technique, the best fit polynomials $A(x)$ and $B(x)$ with minimum order are found to be

$$A(x) = -1.8211 \times x^4 - 54.3739 \times x^3 + 247.4310 \times x^2 - 395.0201 \times x + 287.5556, \quad (6)$$

and

$$B(x) = 26.7396 \times x^4 - 106.8007 \times x^3 + 143.9303 \times x^2 - 67.1442 \times x - 10.9445 \quad (7)$$

Figure 11 Experimental results of the graphical relation between the three parameters

Table 2 Functional relationship between the polynomials A(x), B(x) and the plunger stroke, x

x	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
A	220	160	130	106	82	70	60	60	40
B	-20	-19.3	-19.7	-17.5	-14	-12.7	-12	-14	-7

The family curves of the measured actual force and the simulation pseudo-force by curve-fitting are shown in Fig. 12. The maximal deviation is about 2 N. Fig. 13 shows the block diagram of the force control system using the pseudo-force as feedback signal. The experimental results of the force linearization using the PI- and fuzzy-logic-controller are shown in Figures 14 and 15 respectively. As compared to Figures 5 and 10, it can be observed that the errors near the end-position in Figures 14 and 15 are much more obvious. Apparently, such control errors arise from the numerical errors of curve-fitting as shown in Fig. 12.

Figure 12 Comparisons between the measured actual force and the pseudo-force by curve-fitting

Figure 13 Block diagram of the force control system using the pseudo-force as feedback signal

Figure 14 Experimental results of the force linearization using the PI-controller

Figure 15 Experimental results of the force linearization using the fuzzy-logic-controller

CONCLUSION

In this paper, two different methods to linearize the output force of a switching solenoid have been discussed and successfully implemented. It is worth mentioning that the second method utilizing the pseudo-force as feedback signal has a significant benefit of lower cost. The control error near the end-position, however, is obvious and not negligible. Moreover, the experimental results have also proved that the force oscillation after linearization by using the fuzzy-logic-controller is much smaller than that by using the conventional PI-controller. Such a conclusion is valid for both the first and second method. Figure 16 shows typically the comparisons using the first method. Consequently, another advantage by using the fuzzy-logic-controller is the longer effective linear stroke of the plunger available.

Figure 16 Typical comparisons between the experimental results by using the PI- and Fuzzy-logic-controller

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