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ORIGINAL ARTICLE

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Development of an unconventional electro-hydraulic proportional valve with fuzzy-logic controller for hydraulic presses

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Abstract In this study, an unconventional electro-hydraulic proportional flow control valve based on a switching solenoid and a fuzzy-logic controller is proposed for application to hydraulic presses. The main purpose of this study is the attempt to develop an electro-hydraulic proportional flow control valve with lowest cost. Since the switching solenoid possesses quite nonlinear force/stroke characteristics, it is basically not suitable for the development of hydraulic proportional valves. Therefore, the fuzzy-logic controller is employed to linearize the force/stroke characteristics. The basic idea is the utilization of the numerically estimated pseudo-force as the feedback signal. Finally, this newly developed electro-hydraulic proportional flow control valve is installed in a hydraulic press. Experimental results show that the control of the ram velocity of the press cylinder using the proposed electro-hydraulic proportional flow control valve is quite successful.

Keywords Fuzzy-logic controller · Hydraulic press · Linearization · Proportional valve · Solenoid actuator

1 Introduction

Presses are perhaps the most commonly used machine tools for metal forming [1]. According to different types of actuation, they can be classified as mechanical and hydraulic presses. Some distinct advantages of hydraulic presses over mechanical ones are the simpler design and construction, the linearly variable output press force and ram velocity of the press cylinder, the ready adjustment of the ram position and the more effective protection from overload. Figure 1 shows two typical circuits of hydraulic presses [1]. The first (Fig. 1a) represents a pump-controlled system, in which a complex variable-displacement pump is used to control the output volumetric flow rate in a manner that is proportional to an applied electrical signal. Consequently, the ram velocity of the press cylinder can also be linearly controlled. Besides, a pressure-relief valve is employed in the circuit to control the output press force of the press cylinder. In the second hydraulic circuit (Fig. 1b), however, a simple fixed-displacement pump is utilized. The control of the volumetric flow rate and the ram velocity of the press cylinder is achieved by an electro-hydraulic proportional flow control valve. Therefore, this hydraulic circuit basically represents a valve-controlled system. In addition, it may also be found that a pressure-relief valve and an accumulator are installed in this circuit. The former is employed to control the output press force of the press cylinder, and the latter is charged with high-pressure oil at the beginning and then serves as an auxiliary power source. Thus, the hydraulic pressure required to produce a corresponding output press force is maintained constant and, consequently, a smooth control of the ram velocity of the press cylinder can be obtained.

Generally speaking, the price of a variable-displacement pump is much higher than that of a conventional fixed-displacement pump. Besides, the response speed of a pump-controlled system is much lower than that of a valve-controlled system [2]. Nowadays, therefore, the latter design is still preferred though the former possesses the advantage of energy saving. On the other hand, the valve-controlled hydraulic circuit shown in Fig. 1b requires an electro-hydraulic proportional flow control valve, which is the most important but expensive component in the circuit. Figure 2 shows the schematic structure of the valve. It can be observed that such a valve consists of two parts. One is the proportional valve body, in which the proportional solenoid is utilized to regulate the opening area of the valve orifice. The other is the pressure compensator, which maintains a constant pressure drop across the valve orifice in case of possible variations of external loads.

Figure 3 shows the structures and characteristics of two commonly used solenoid actuators [2]. The first is the switching solenoid, which is widely applied to the design of traditional hydraulic directional control valves. The second is the propor-

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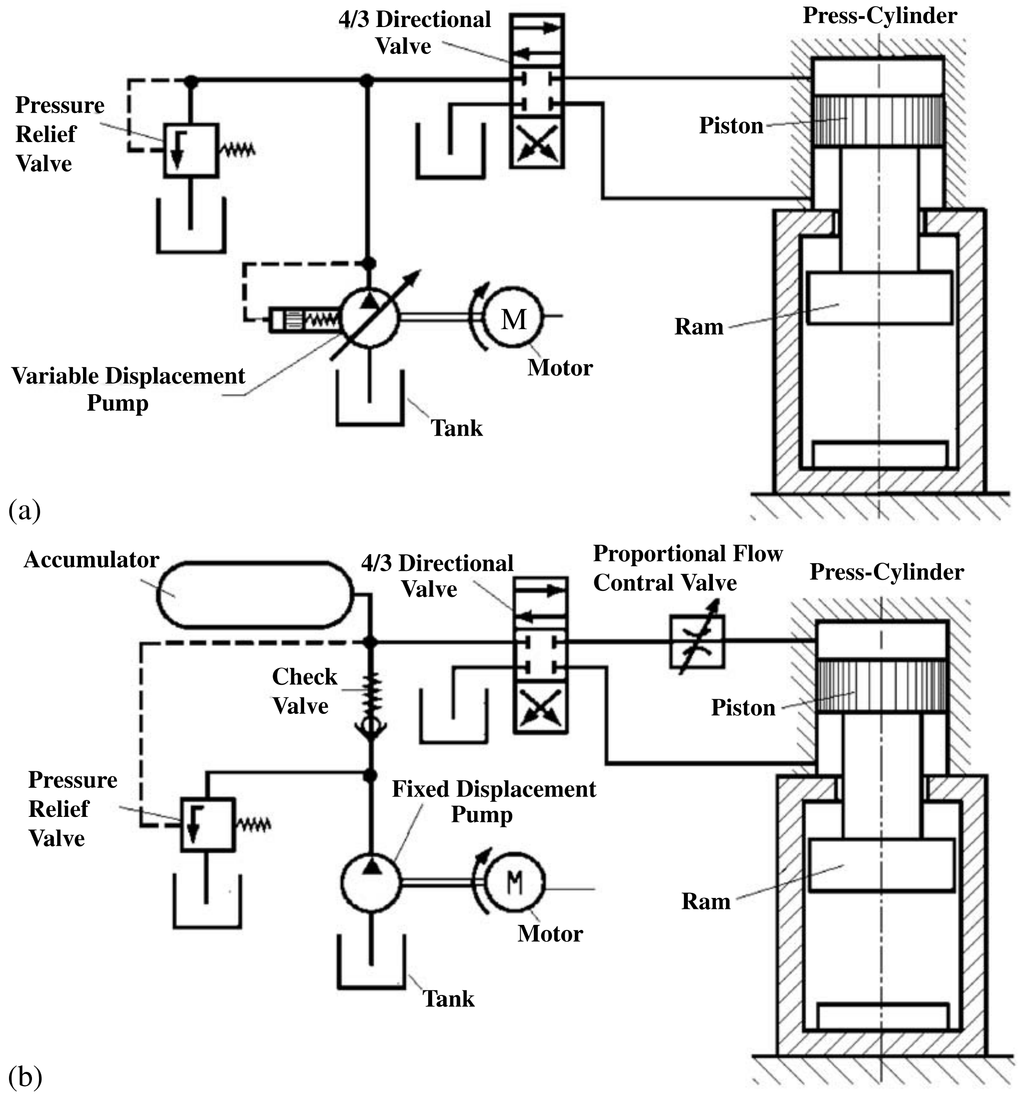


Fig. 1. Two typical circuits of hydraulic presses

tional solenoid, which is the standard component for the development of electro-hydraulic proportional valves. As shown in Fig. 3, the switching solenoid and the proportional solenoid have quite different force/stroke characteristics, though they possess almost the same structure. In detail, the former possesses a highly nonlinear behavior regarding the force/stroke characteristic; the static force/stroke characteristic of the latter, however, is quite linear. Such a linear force/stroke relation of the proportional solenoid is the key requirement for the design of electro-hydraulic proportional valves. For example, the valve spool, which is subjected to a constant force in the linear working range, reaches a definite position in the valve body according to Hooke's law. This definite position of the spool signifies a definite opening area of the valve orifice. Furthermore, it is also observed from Fig. 3 that the relation between the output force and the input current is quite linear. Consequently, the opening area of the valve orifice is continuously variable and is proportional to the input current. This is exactly the basic function of electro-hydraulic proportional valves.

The prerequisite to utilize the low-cost switching solenoid instead of the high-cost proportional solenoid is the linearization of its force/stroke characteristics. Previous reports [3–5] concerning the linearization of the force/stroke curves of switching solenoids can be found in the 1990s. However, only the linear proportional–integral controller was employed in these papers. The results of the force linearization were also not fully satisfactory. In this paper, therefore, a nonlinear fuzzy-logic controller together with a closed-loop force-control scheme are proposed to linearize the force/stroke characteristics. Moreover, instead of the installation of an expensive force sensor, this closed-loop force-control scheme utilizes the numerically estimated pseudo-force as the feedback signal to minimize the cost of implementation. In the following, the experimental test device for solenoid actuators is firstly outlined.

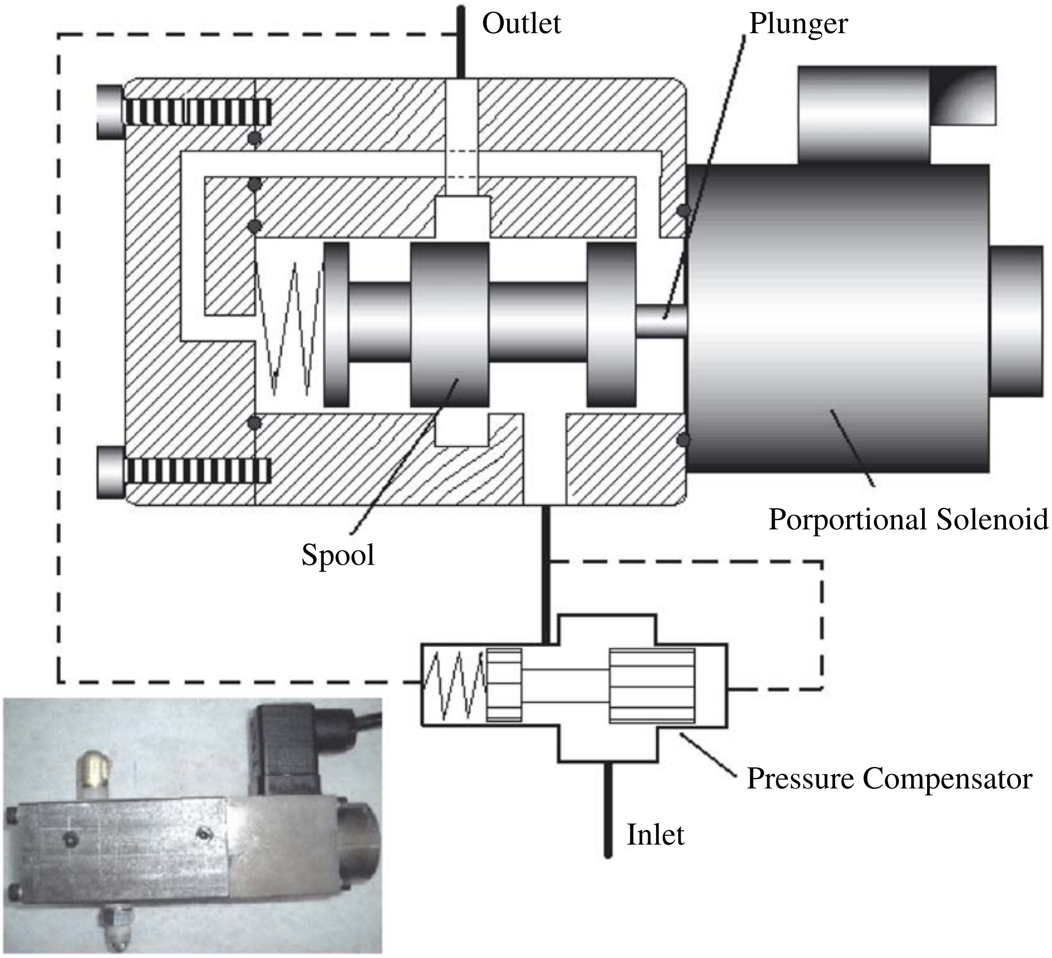
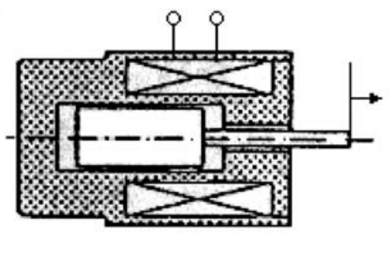
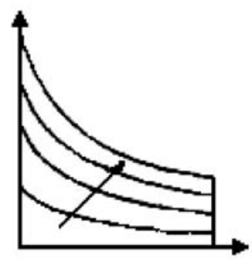
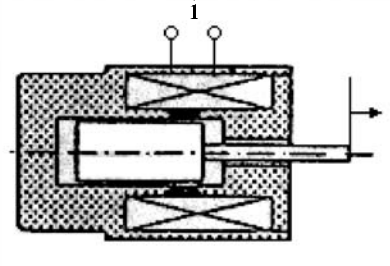
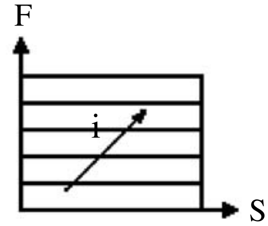


Fig. 2. The schematic structure of the proportional flow control valve

Fig. 3. The structure and characteristics of the switching solenoid and the proportional solenoid

	Stucture	**Force/stroke Characteristics**	**Price ratio**
Switching Solenoid			**1**
Proportional Solenoid			**10**

2 Experimental test device

The static test device for solenoid actuators is shown in Fig. 4. An open-loop-controlled micro-stepping motor (American Precision Industries, CMD-260) is utilized to control the plunger position of the tested solenoid. In detail, the angular displacement of the micro-stepping motor is proportional to the number of pulses of the square-wave signal sent to the driver. The direction of rotation can be easily controlled by sending a Hi (5 V) or Lo (0 V) signal to one input port of the driver. In addition, a ball screw is attached to the rotor, which transforms the angular motion into a rectilinear movement. Besides, this test device provides a position sensor (RDP-LVDT-D2/200) as well as a load cell (BAB-10M) for the measurement of the position and the output force of the plunger. In the practical application, however, the load cell is not necessary and a low-cost potentiometer is used to measure the plunger position.

To measure the coil excitation current, a series resistor of 10 Ω is used in the electric circuit. To produce the linearly controllable input current as well, a voltage-to-current transducer (i.e. amplifier) is employed. Finally, the control of the unit as well as the acquisition and processing of the measured data are all integrated in a Pentium-III-based software controller. Figure 5 shows the measured nonlinear force/stroke characteristics of the tested switching solenoid, which is originally developed for NG02 hydraulic directional valves.

In the following sections, two procedures involved in the linearization of the force/stroke characteristics of the switching solenoid are described. The first is the estimation of the pseudo-force signal and the second is the introduction of a fuzzy-logic controller for the closed-loop force control of the switching solenoid.

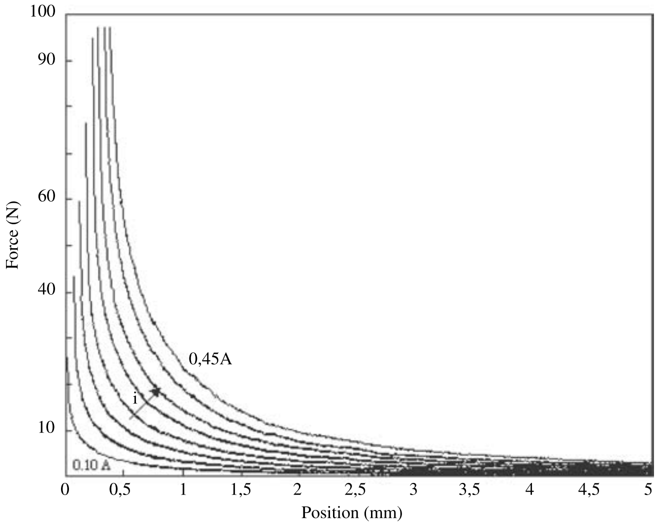


Fig. 5. The measured nonlinear force/stroke characteristics of the tested switching solenoid

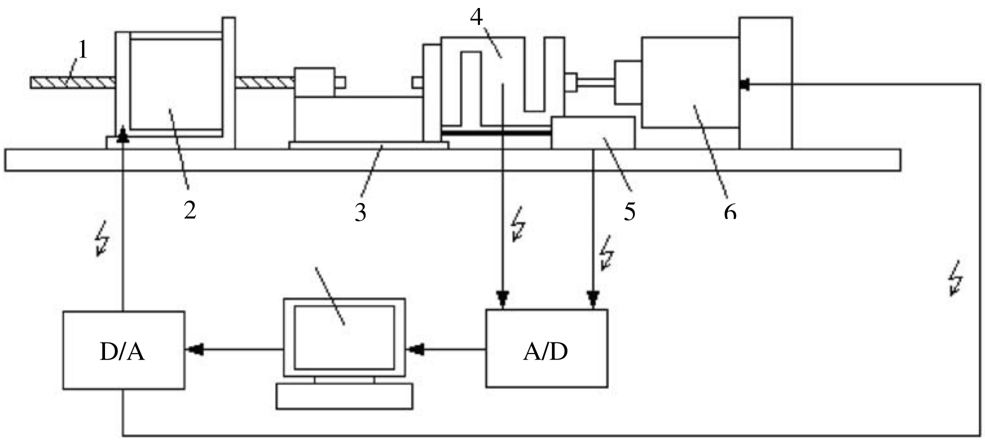
3 Estimation of the pseudo-force feedback signal

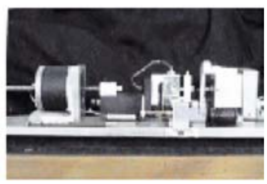
Let the pseudo-force, F_p, be a function of the plunger position, x_m, and the coil current signal, i_m; thus,

$$F_p(x_m, i_m) = A(x_m)i_m + B(x_m). \quad (1)$$

From the experimental results shown in Fig. 6, Table 1 can be established, in which three parameters are involved, the plunger position, the output force of the plunger and the coil current. By a curve-fitting technique, the best-fit polynomials $A(x_m)$ and

Fig. 4. The static test device for solenoids





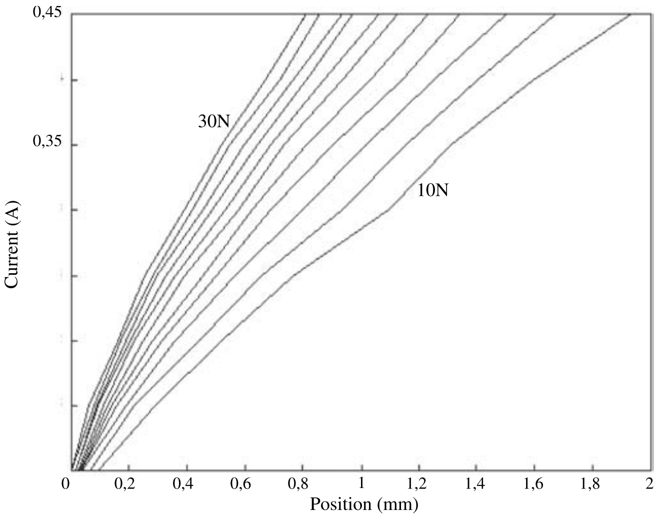


Fig. 6. Experimental results of the graphical relation between the three parameters

$B(x_m)$ with minimum order are found to be

$$A(x_m) = -1.8211x_m^4 - 54.3739x_m^3 + 247.4310x_m^2 - 395.0201x_m + 287.5556 \quad (2)$$

and

$$B(x_m) = 26.7396x_m^4 - 106.8007x_m^3 + 143.9303x_m^2 - 67.1442x_m - 10.9445. \quad (3)$$

The family curves of the measured actual force and the simulation pseudo-force by curve fitting are shown in Fig. 7. The maximal deviation is only about 2 N. Since the position of the plunger, x_m, and the coil current, i_m, are easily measured and usually known, the output pseudo-force, F_p, can be numerically derived from Eqs. 1–3.

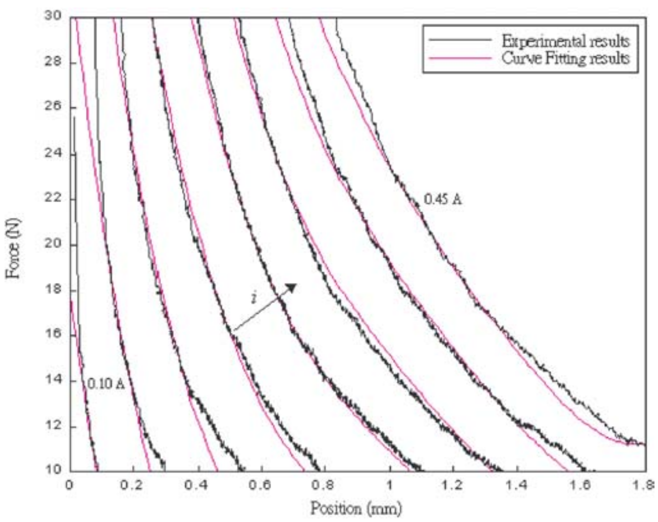


Fig. 7. Comparisons between the experimentally measured actual force and the estimated pseudo-force by curve fitting

Table 1. Functional relation between the polynomials and the plunger stroke

x_m	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	−19.3333	−19.6667	−17.5	−14	−12.6667	−12	−14	−7

4 Design of the fuzzy-logic controller

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 knowledge and defuzzification of the rule-based control signal.

(a) Fuzzification
In this study, the two input signals to the fuzzy controller are the force error signal, $e(k)$, and its change signal, $\Delta e(k)$:

$$e(k) = F_d - F_p, \quad (4)$$

$$\Delta e(k) = e(k) - e(k-1). \quad (5)$$

Here F_d: desired force signal,
F_p: estimated pseudo-force signal.

Figure 8 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 2 shows the definition of the rules.

(c) Defuzzification
The defuzzification is to transform the control signal into an exact control output. In the defuzzification, the method of

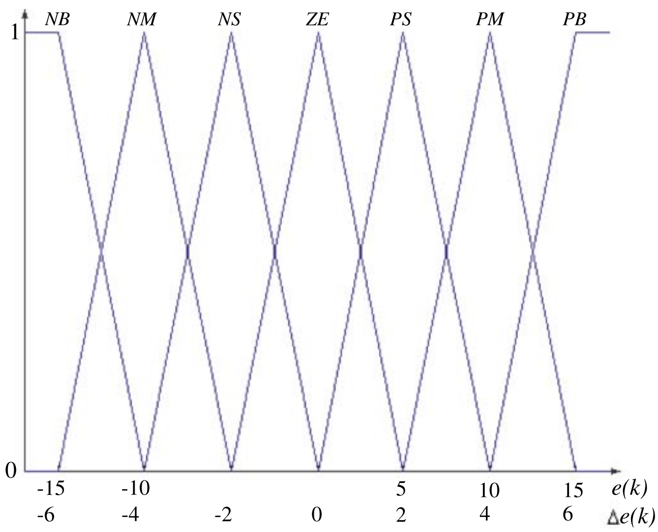


Fig. 8. Fuzzy membership function for two input signals

Table 2. 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
	ZS	PB	NB	NM	NS	ZE	PS	PM
	NM	PM	PB	NB	NM	NS	ZE	PS
	NB	PS	PM	PB	NB	NM	NS	ZE

center of gravity is used:

$$y = \frac{\sum_{i=1}^{n} W_i B_i}{\sum_{i=1}^{n} W_i}, \tag{6}$$

where y: the output of the fuzzy controller,
W_i: the degree of firing of the ith rule,
B_i: the centroid of the consequent fuzzy subset of the ith rule.

The output actuating signal of the fuzzy controller, $u(k)$, is defined as

$$u(k) = u(k-1) + \Delta u(k). \tag{7}$$

Figure 9 shows the output membership function for the actuating signal change, $\Delta u(k)$.

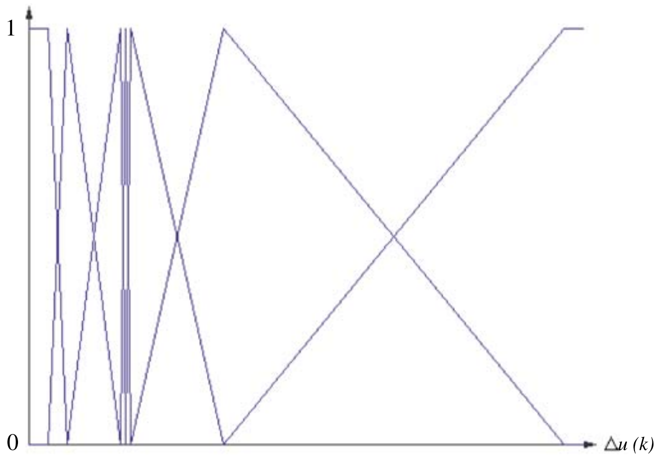


Fig. 9. Output membership function for the actuating signal change

5 Experimental results of force linearization by pseudo-force feedback

Figure 10 shows the block diagram of the force-control scheme using the estimated pseudo-force as its feedback signal. The corresponding experimental results of the force linearization using the fuzzy-logic controller are shown in Fig. 11. In the range of plunger positions $0.15\,\text{mm} < x_\text{m} < 0.95\,\text{mm}$, the experimentally measured force signals are almost straight and horizontal lines, which signify the successful linearization of the force/stroke characteristics. In the same range, moreover, the estimated pseudo-force also agrees very well with the experimental one. This further proves the validity of the model described by Eqs. 1–3. However, it is also observed that the measured force signals in the range of plunger positions $0\,\text{mm} < x_\text{m} < 0.15\,\text{mm}$ are not properly linearized. This is chiefly because of the obvious difficulties of compensating the highly nonlinear and almost vertical force/stroke curves in this range, as shown in Fig. 5. Table 3 shows the comparisons of the technical data between the conventional proportional solenoid and the new proportional switching solenoid. Because the output flow rate through the valve orifice with a constant pressure drop is proportional to the plunger stroke [2] and the linear working stroke of the new proportional switching solenoid is shorter, the available flow rate through the

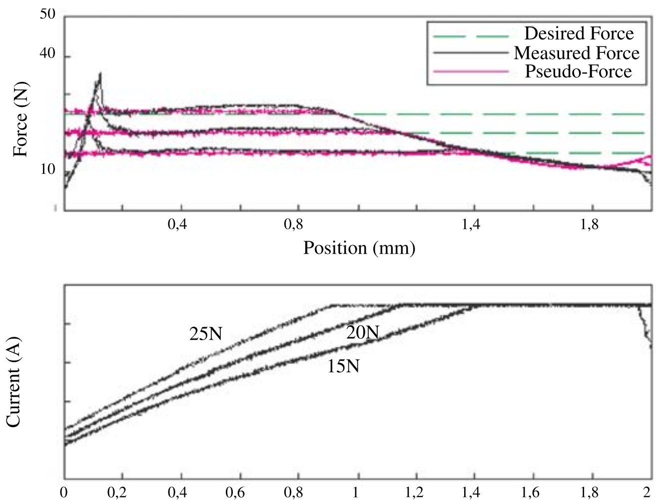


Fig. 11. Experimental results of the force linearization using the fuzzy-logic controller

Fig. 10. Block diagram of the force-control scheme using pseudo-force as feedback signal

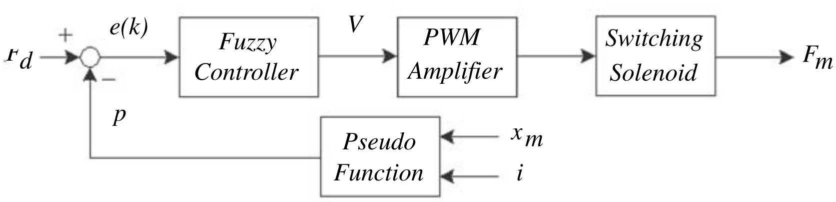


Table 3. Comparisons between the two proportional solenoid actuators

Type	Conventional proportional solenoid (Magnet-Schultz GRF045)	New proportional switching solenoid (Seven Ocean NG02)
Linear working stroke	3 mm	0.8 mm
Linear maximal output force	65 N	25 N
Maximal excitation current	0.81 A	0.45 A

newly developed proportional flow control valve is expected to be smaller. Nevertheless, a low-cost proportional flow control valve using the new proportional switching solenoid instead of the conventional proportional solenoid has been successfully developed.

6 Installation in a hydraulic press and experimental results

A valve-controlled hydraulic press is used in the laboratory to verify the performance of the proposed unconventional proportional flow control valve. The piston diameter and the maximal stroke of the ram are 350 mm and 250 mm, respectively. The maximal ram velocity is 300 mm/min, corresponding to a volumetric flow rate of 30 l/min. The output press force reaches 2000 kN if the supply hydraulic pressure is set to be 210 bar. To measure the ram velocity, a linear potentiometer is firstly utilized to acquire the signal of the ram position. Then, the ram velocity is numerically obtained by

$$v_{\mathrm{m}}(k) = \frac{x_{\mathrm{m}}(k) - x_{\mathrm{m}}(k-1)}{T_{\mathrm{s}}}, \tag{8}$$

where v_{m}: measured ram velocity,
T_{s}: sampling time.

Figure 12 shows the experimental step responses of the ram velocity to three different force inputs. Because the pressure compensator maintains a constant pressure drop across the valve orifice, the output flow rate is proportional to the stroke of the solenoid's plunger. It is thus observed that the ram velocity is controllable in a manner that is proportional to the desired input force and the performances are satisfactory. This proves the feasibility of the attempt to develop a low-cost unconventional proportional flow control valve. On the other hand, however, the maximal ram velocity corresponding to the maximal desired input force of 25 N reaches only 96 mm/min, which is approximately 1/3 of the original one.

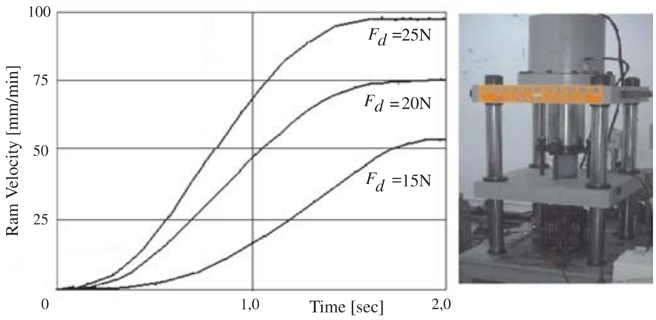


Fig. 12. Experimental step responses of the ram velocity to three different force settings

7 Conclusion

In this paper, a new proportional switching solenoid has been successfully developed and applied to the design of an unconventional proportional flow control valve for hydraulic presses. Three conclusions may be drawn from this research.

Both attempts to use the numerically estimated pseudo-force as the feedback signal and to linearize the force/stroke relation of the switching solenoid by a fuzzy-logic controller were successful.

The newly developed unconventional proportional flow control valve for hydraulic presses possesses a remarkable advantage of lower cost, because the price of a switching solenoid is only about 10% of that of a proportional solenoid.

The available flow rate through the newly developed proportional valve is smaller than that through the original one. This may be regarded as the cost of linearization. Such a defect, however, may be easily overcome by choosing a switching solenoid having a larger output force for the linearization, like the switching solenoid for NG03 hydraulic valves.

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