Review

Paper

Letter

Converting a Switching Solenoid to a Proportional Actuator

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Solenoids are presently used as cheap and robust switching components. These are variable reluctance devices with their characteristics dictated by a highly nonlinear magnetic circuit. This paper describes the research work done on converting a switching solenoid into a proportional device. It first investigates the magnetic characteristics of a solenoid, followed by developing a control model for the device. Based on this model, a dual rate cascade control scheme with a nonlinear force mapper is proposed for proportional control. This scheme is tested out by simulation and implemented on a Digital Signal Processor based controller.

Keywords : Solenoid, Proportional Actuator, Nonlinear Control

1. Introduction

Solenoids are presently used as mechanical switching components only. They are simple in construction, rugged, relatively cheap to produce, and can be totally enclosed and sealed quite easily. However, these are not suitable for use in proportional control, largely due to the nonlinearity of their magnetic circuit and force equations.

Fig. 1 shows the typical construction of a linear and limited travel solenoid valve. The total travel of such a solenoid is very short : in most cases it is less than one centimetre.

Present proportional actuators employ moving coil techniques working under constant magnetic field. This arrangement decouples the control from the nonlinear magnetic behaviour. The solenoid is a variable reluctance device with its force derived from the change in its magnetic circuit[1]~[3]. Since the magnetic behaviour is non linear, simple linear feedback control is not adequate. Most position control systems for linear motors use a heirachical control structure with separate control loops for current, velocity and position. For each loop, only one control variable is required to regulate. This method does not work in solenoids, since the force produced on the plunger is a function of both position and current.

There exist little literature on the continuous control of solenods. The existing large body of literature on variable reluctance and switched reluctance motors are not directly useful to the development of proportional solenoids. The paper describes a method to convert an on/off switching solenoid into a proportional actuator by the use of intelligent control. The advantages gained from this work are : (i) low cost, since proportional actuators based on linear motors are more expensive than solenoids, (ii) higher reliability and little need of maintenance, due to the simple construction of solenoids, (iii) easy incorporation into systems, because of a solenoid's compact design and robust construction.

Section 2 examines the magnetic and control characteristics of a solenoid. A control model, including nonlinear magnetic characteristics, is developed. Section 3 describes the dual rate cascade control strategy, and its mechanism of nonlinear magnetic characteristics compensation. Finally, section 4 reports the simulation and hardware implementation results of such a controller on a industrial switching solenoid.

2. Development of the Control Model

Before any form of control strategy is proposed, a full control model of the solenoid need to be developed. Aolenoid is a variable reluctance device with its force derived from the change of magnetic flux linkage. Therefore, the flux linkage relationships with current and position form the bases of the full control model[3]~[5].

2.1 Static and Dynamic Characteristics of a Solenoid

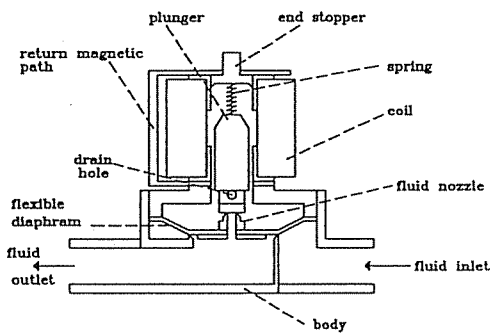A solenoid has a resistive and inductive circuit. Its

Fig. 1. Construction of a solenoid valve.

Fig. 2. Flux linkage vs position and current.

voltage equation can be expressed as :

$$V = Ri + \frac{d\lambda}{dt} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where V is the terminal voltage and R is the resistance of coil. The flux linkage λ is a variable dependent on the current of the coil i and the air gap distance x. Therefore the voltage equation can be rewritten as :

$$V = Ri + \left(L_e + \frac{\partial\lambda(x, i)}{\partial i}\right)\frac{di}{dt} + \frac{\partial\lambda(x, i)}{\partial x}\frac{dx}{dt} \cdots\cdots (2)$$

L_e is the inductance of the external circuit. Of the three terms in (2), the first term is the resistive voltage drop. The second term is the inductive voltage due to change of current. The third term is known as the motional e. m. f. and is caused by the motion of the plunger. Equation (2) can only be solved if the magnetic characteristics of the solenoid are known.

On the mechanical side, the solenoid can be represented by a mass spring system :

$$m_p \ddot{x} = F_{\text{mag}} - K_s x - m_p g \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where m_p is the mass of the plunger, K_s is the spring constant, g is the gravitational constant and F_{mag} is the force produced by magnetic field when the coil is energised. F_{mag} can be calculated from the co-energy W' [6]. The co-energy can be estimated from the integration of flux linkage against current :

$$F_{\text{mag}} = \frac{\partial W'(x, i)}{\partial x} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

$$W'(x, i) = \int_0^i \lambda(x, i) \cdot di \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Since the variables i and x are fully independent and separable in relation to $\lambda(x, i)$, it is permissible to differentiate under the integral sign. Equations (4) and (5) become :

$$F_{\text{mag}} = \int_0^i \frac{\partial\lambda(x, i)}{\partial x}\bigg|_{i=\text{const}} di \cdots\cdots\cdots\cdots (6)$$

For instantaneous value of F_{mag}, when x does not change during a short period of time, (6) can be written as :
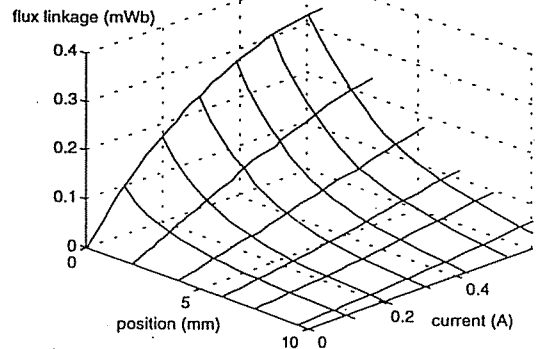
$$F_{\text{mag}} = \frac{\partial\lambda(x, i)}{\partial x} \cdot i \cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

From equations (2), (3), and (7) we can write a non linear state model :

$$\frac{dx}{dt} = v \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (8)$$

$$\frac{dv}{dt} = \left(\frac{\partial\lambda(x, i)}{\partial x} i - K_s x - m_p g\right)\frac{1}{m_p} \cdots\cdots\cdots (9)$$

$$\frac{di}{dt} = \left(V - Ri - \frac{\partial\lambda(x, i)}{\partial x}\frac{dx}{dt}\right)\frac{1}{L_e + \frac{\partial\lambda(x, i)}{\partial i}} \cdots (10)$$

In (8) to (10), $\frac{\partial\lambda}{\partial x}$ and $\frac{\partial\lambda}{\partial i}$ are obtained from a model of the magnetic characteristics. Flux linkage relationships with current and position need to be found to complete the state model.

2. 2 Measurement of Flux

Many methods are available on measuring the magnetic characteristics of switched reluctance motors [11],[12]. This paper uses a measurement technique based on a. c. excitation and induced e. m. f. measured by a search coil wound on the solenoid's plunger [1].

To measure the induced flux, an a. c. voltage is fed into the solenoid coil, with the plunger fixed at predetermined positions, when the induced voltage waveform from the search coil and the current waveform from the solenoid are measured. This measurement process is repeated for all the positions and currents of the solenoid.

Flux and flux linkage through the plunger can be obtained from the following equations :

$$\Phi(t) = -\frac{1}{N_s}\int_0^t e(t) \cdot dt \cdots\cdots\cdots\cdots\cdots\cdots (11)$$

$$\lambda(t) = N \cdot \Phi(t) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (12)$$

where $\Phi(t)$ is the flux, $\lambda(t)$ is the flux linkage, $e(t)$ is the voltage output from the search coil, N is the number of turns of the solenoid coil, and N_s is the number of turns of the search coil. This calculation results in a series of hysteresis loops at different currents and position. By
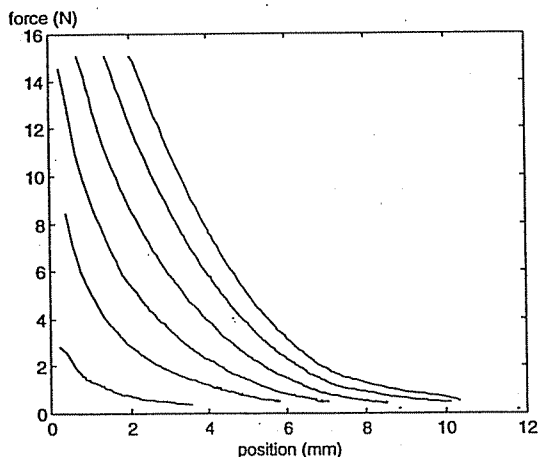
Fig. 3. Variation of force against position and current.

Fig. 4. Block diagram of the control system.

Fig. 5. The current controller.

joining the vertices of the hysteresis loops, the magnetic characteristics of flux linkage versus current and position can be obtained, as shown in Fig. 2.

Change of flux linkage creates force on the plunger, as described in (7). Therefore force is also a two dimensional relation with current and position as shown in Fig. 3. The plot is obtained by actual measurement of static force against position and current. Alternatively, the force function can be calculated by applying (7) to the graphic polot of Fig. 2.

3. The Proportional Actuator

There is little in recent literature which deals with proportional control of solenoids. For the related problem of rotary switched reluctance motors, M. Illic-Spong et al[7],[8] used feedback linearizing technique to tackle the problems of nonlinearity. Though it has produced promising results in simulation, the method is too complicated to implement in real time. D. G. Taylor[9] used reduced order composite control for the variable reluctance motor, however, external analogue hardware is required to linearise the current voltage relationship of the switched reluctance motor.

Exploiting the fact that the current dynamics is at least an order of magnitude faster than the mechanical dynamics, this paper proposes a dual rate cascade control approach. A fast inner loop current controller is employed to regulate the current-voltage nonlinearities of the solenoid, while a slower outer loop trajectory controller is used to control the mechanical dynamics. On top of this, a nonlinear function is included to compensate the nonlinearities of force against current and position. Fig. 4 is the overall block diagram of the control system.
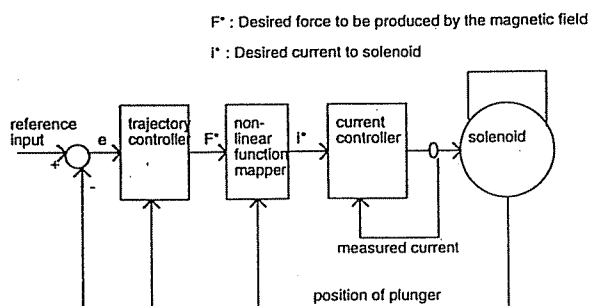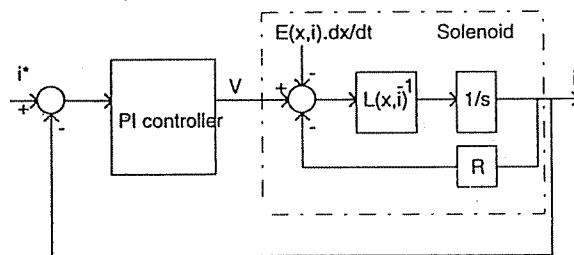
3.1 The Current Controller

A current controller is employed to linearise the current-voltage relationship of the solenoid. A simple PI controller has been used for this purpose.

Position can be assumed to be stationary during the control time frame of the current controller, since current dynamics are much faster than mechanical dynamics. Thus (2) can be simplified to :

$$V = Ri + L(i)\frac{di}{dt} + E(i)\frac{dx}{dt} \quad \cdots\cdots\cdots\cdots\cdots\cdots (13)$$

where $L(i) = L_e + \frac{\partial \lambda}{\partial i}$ and $E(i) = \frac{\partial \lambda}{\partial x}$

$E(i)$ constitutes a disturbance term to the current controller as shown in Fig. 5. However, simulation studies shows that under normal operation, $E(i)$ constitutes less than 2% disturbance to the overall equation. Moreover, $E(i)$ is approximately constant over the operation range of i, as shown in Fig. 2. The figure also shows that $L(i)$ is also approximately constant within the operating range, except when $x = 0$. Thus, a PI controller is sufficient to control a solenoid which essentially has a resistive-inductive loading.

Standard Ziegler Nichols procedure has been used to tune the controller. Since the controller is least stable when inductance is large, the current controller should be tuned at $x = 0$, when the inductance is at its largest.

Solenoids have large inductance ; to avoid excessive saturation to the integrator during step inputs, antiwindup features should be present in the controller. Fig. 6 is the dynamic response of the current controller with plunger at $x = 0$ and $x = 10$ mm. The worst case step
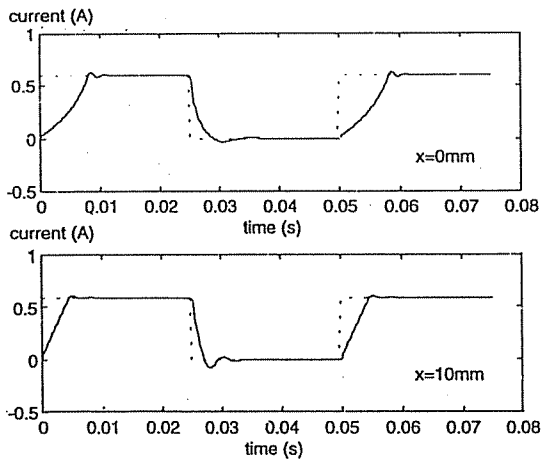
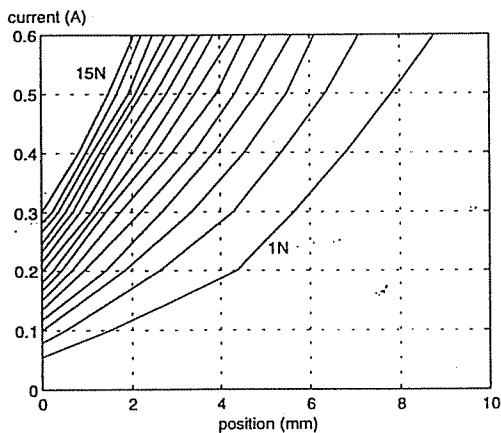Fig. 6. Response of the current controller (Experimental results)..

Fig. 7. Measured force profile of the solenoid.

response time is less than 0.01 sec, and the tracking path is reasonably accurate.

3.2 The Nonlinear Force Compensation Mapper

The nonlinear force compensation mapper bridges the link between the trajectory controller and the current controller. It receives force demands from the trajectory controller and outputs desired current set points to the current controller. Since the relations of force, current, and position are nonlinear in nature, a look-up table is used to translate the force and position inputs to desired current outputs.

Fig. 7 is the force profile of the solenoid, this information is stored as a two dimensional look-up table. A 20 ×20 elements look-up table with two dimensional linear interpolation is sufficient to describe the force profile with an accuracy of ±5 %[10].

3.3 The Trajectory Controller

The trajectory controller forms the essential part of the slow sub-system. It is a typical PID controller. The controller's operation is based on the assumption that the current controller has perfect tracking capability,

Table. 1.

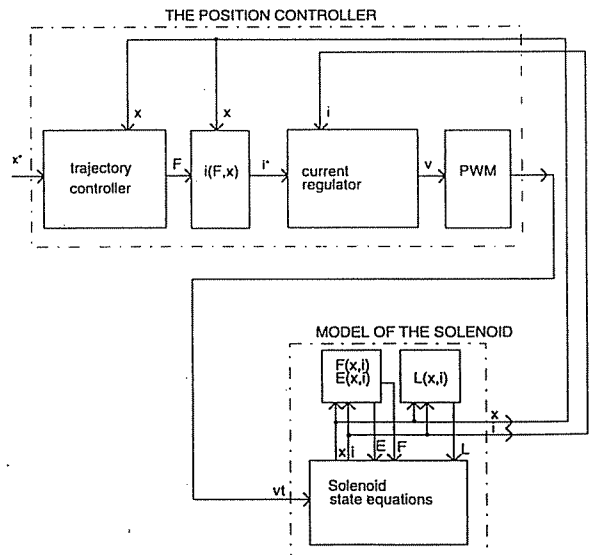| Make	Goyen Controls
Type	2 stage switching solenoid valve
Stroke length	10 mm
Operating voltage	24 V d.c.
Maximum current	0.6 A
Resistance	40 ohms
Inductance	0.35-1.1 H
No of turns of coil	2240

Fig. 8. Simulation of the controller.

and the non linear function mapper generates the linearised current command i^* to the current controller. Equation (7) is rearranged to form the mechanical equation:

$$F = m_p \frac{dv}{dt} + K_s x + m_p g \quad \cdots\cdots\cdots\cdots\cdots\cdots (14)$$

The required force is calculated from the plunger's position x, and acceleration, dv/dt. The acceleration value, derived from the output of the PID controller, is fed into equation (14) to calculate the required force F.

4. Implementation and Results

A typical industrial switching solenoid valve is employed to implement the proportional actuator. This type of solenoid is being used in many types of industrial applications. Its construction is shown in Fig. 1. The solenoid has the specifications given in Table 1.

4.1 Simulation of the Controller

The control system including full model of the solenoid is simulated to find out the performance of the system. Fig. 8 is the block diagram for the simulation.

Results of the simulated trajectory response and step response of the controller is shown in Fig. 10.
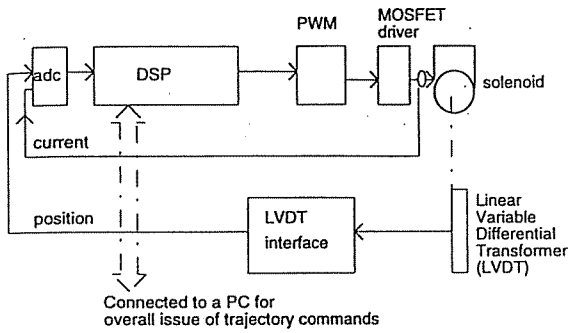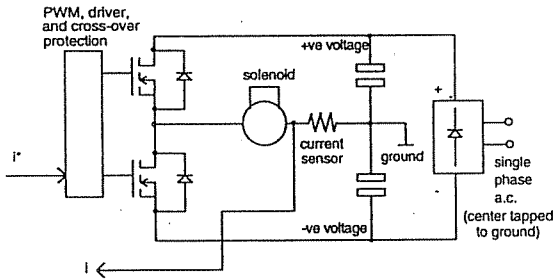
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Fig. 9. Setup of the control system.

Fig. 10. The output stage.

Table. 2.

Make and Type	Radio Spares miniature LVDT, model no: DFg 5
Range	±5 mm
Resolution	0.3% of f. s. d
Mass	4.1 g

(a)

(b)

Fig. 11. Simulated responses of the controller: (a) step response, (b) trajectory following.
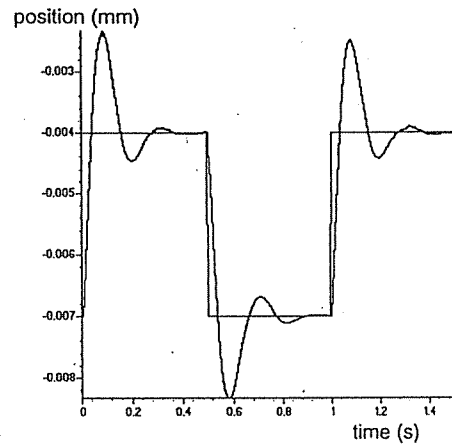
4.2 Hardware Setup

The overall hardware setup is shown in Fig. 9. A Digital Signal Processor is used to implement the controller in hardware. The current to the solenoid is supplied from a centretapped, half bridge power MOSFET inverter circuit with ±65 V supplies, as shown in figure 10. The power MOSFETs are switched at 12.5 kHz from a pulse width modulator (PWM). As for the Digital Signal Processor, the outer control loop samples at 1 kHz, while the inner control loop samples at 4 kHz.
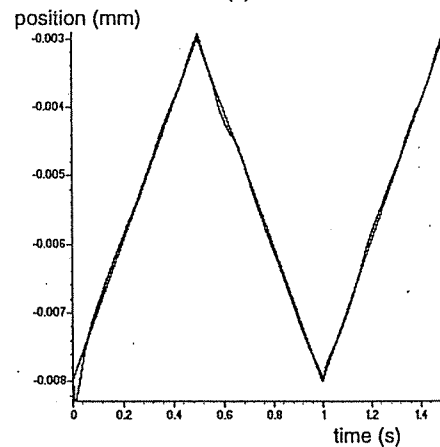
To measure the position of the plunger, a nylon shaft was attached to one end of it. The other end of the nylon shaft was attached to a linear voltage differential transformer (LVDT). Care was taken to keep the total connected mass to a minimum in order not to alter the dynamics of the plunger significantly. The specifications of the LVDT are given in Table 2.

4.3 Results

Fig. 11 shows the simulated step response and trajectory tracking response of the proportional solenoid. The simulation results show that the plunger can track the trajectory path command accurately. These results

are very similar to the results obtained from hardware implementation, which are shown in Fig. 12. This confirms that the solenoid's model is valid and is sufficiently accurate.

Both simulation and actual implementation results show that the proposed control scheme can control the solenoid with high accuracy, speed and stability.

In spite of the good results, there are some limitations on the control range of the proportional solenoid. It has been found that the hysteresis loop characteristics of the solenoid changes at various plunger positions[1]. The hysteresis effect is largest at position $x=0$. This effect reduces rapidly as x moves away from the zero position. At 0-1 mm travel range, the hysteresis effect is significant and affects the performance of the controller. It produces a "latching function" on the motion of the plunger, as shown in Fig. 13. To avoid this hysteresis effect, it is best not to attempt proportional control within the 0-1 mm travelling range.

Fig. 7 is the force profile of the solenoid at different currents and positions. It shows that when position is greater than 9 mm, force exerted on the plunger can
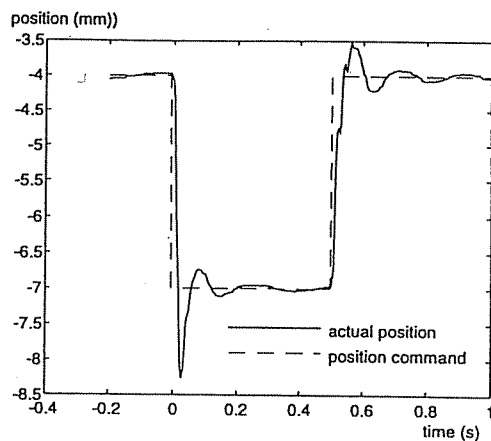
(a)
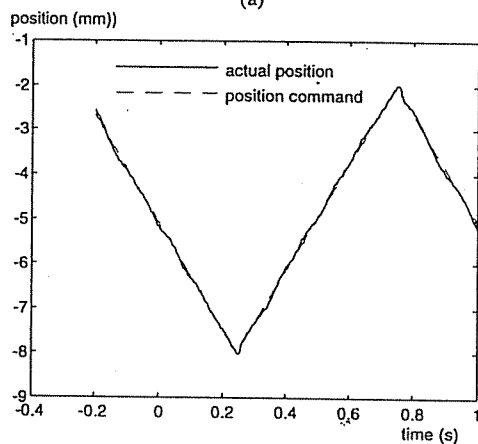
(b)

Fig. 12. Experimental responses of the controller :
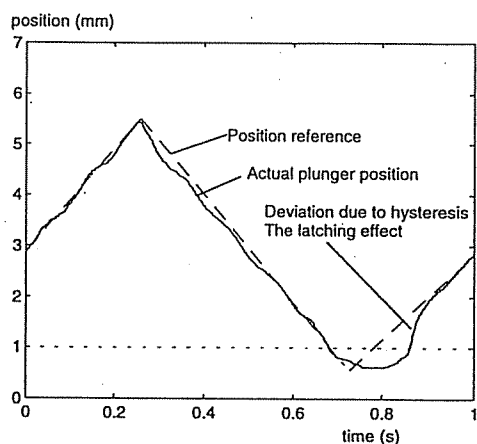(a) step response, (b) trajectory following.

Fig. 13. The effect of hysteresis when plunger is near the zero air gap region.

never be greater than 1N, even when maximum current is applied. The force capability of the solenoid is very limited at this end. Therefore it is best to avoid the 9-10 mm control region.

To summarise, the proportional solenoid should have a limited travel range of 1-9 mm (i. e. 8 mm stroke length), because of hysteresis and limited force capability. In spite of these restrictions, a 8 mm stroke length
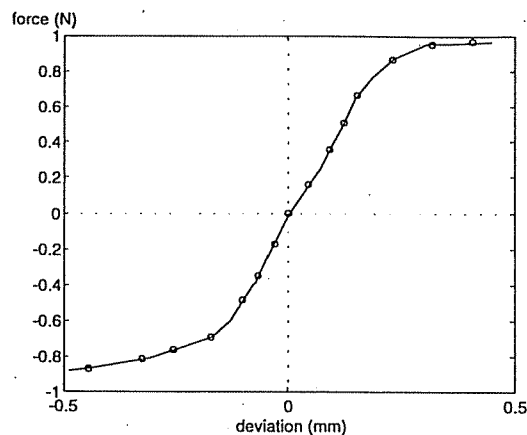

Fig. 14. Stiffness characteristic of the proportional actuator around a reference position of 5 mm.

proportional solenoid is considered to be more than adequate for most industrial applications.

Fig. 14 shows the stiffness of the control system. The restoring force acting on the plunger has been measured when the plunger is deviated from its original set-point position of 5 mm. There is a large force change around the ±0.1 mm region, then the force change becomes more gentle outside this region. Overall, the reasonably high stiffness of the system indicates that the system can be controlled to a high degree of accuracy.

5. Conclusion

This paper demonstrates a method of converting a normal switching solenoid to work as a proportional actuator. The control characteristics of the solenoid is investigated and a nonlinear control model is obtained. Then, an intelligent control strategy based on dual rate cascade control and force compensation is proposed. This control method is implemented on a typical industrial solenoid valve. Both computer simulation and hardware implementation confirm that the solenoid can be controlled with reasonably good accuracy. However it is best to avoid travelling into the two end limits, because of hysteresis and limited force range.

The proposed method is simple, easy to implement, and the control algorithm can easily be transported to a low cost processor.
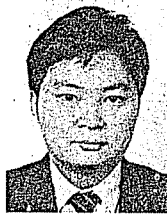
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