Proportional Control of a Solenoid Actuator

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***Abstract*- Solenoids are non linear actuating devices normally used in a switching mode. This paper proposes a dual rate cascade control for converting a switching solenoid into a proportional actuator. A fast inner loop current controller and a slower PID outer loop trajectory controller are employed. A simple static nonlinear map is used to partially linearise the system. This method results in a proportional actuator which is effective and practical.**

INTRODUCTION

SOLENOIDS are widely used as switching actuators. They are simple in construction, rugged, and relatively cheap to produce. This paper describes part of a project which aims to convert switching solenoids into proportional solenoids using appropriate control strategies. This is a non trivial task because of the highly non linear magnetic characteristic of the device [1,3]. A solenoid is a variable reluctance device which produces force from its magnetic flux [2]. Since the magnetic behaviour is non linear [3,4,5], simple linear feedback control is not adequate. In this paper we propose dual rate cascade control with the magnetic nonlinearities partially compensated by a static nonlinear function.

CONTROL CHARACTERISTICS OF THE SOLENOID

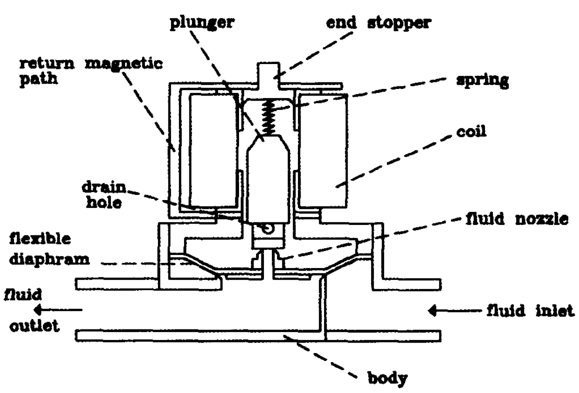

Figure 1 A two stage solenoid valve

Figure 1 is a diagram of a typical industrial two stage solenoid valve. The plunger retracts inward when the coil is energised, and extends outward by releasing the energy from the spring. Total travel of the plunger is very short: in most cases it is limited to less than one centimetre.

MODEL

A dynamic model for such a solenoid was presented in [3]. In this section, the model is briefly reviewed.

The voltage applied to the solenoid coil, V, is

$$V = Ri + \frac{d\lambda}{dt} \tag{1}$$

where i is the current, R is the resistance of the coil, and λ is the flux linkage. The flux linkage is not fully coupled to the magnetic circuit and is dependent on the current of the coil and the air gap distance x. Equation (1) can be expanded as:

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

where an external inductance term L_e represents the leakage. On the mechanical side, the solenoid is represented by a second order linear system:

$$m_p \ddot{x} = F - K_s x - F_d \tag{3}$$

where m_p is the mass of the plunger, K_s is the spring constant, F is the force produced by the magnetic field, x is the displacement of the plunger and F_d is a load force which may include the gravitational force.

The force produced by the magnetic field can be calculated from the co-energy W' where [6]:

$$F = \frac{\partial W'(x,i)}{\partial x} \quad \text{and} \quad W'(x,i) = \int_0^i \lambda(x,i)di \tag{4}$$

From Equation (4), the instantaneous value of F can be re-written as:

$$F = \frac{\partial\lambda(x,i)}{\partial x} \cdot i \tag{5}$$

Flux linkage has a nonlinear relationship with current and with position. These relationships can be obtained experimentally [3] and are of the form shown in Figures 2 and 3.

From equations (1)-(5), a set of state equations can be formed:

$$\frac{dx}{dt} = v \tag{6}$$

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$$\frac{dv}{dt} = \frac{F - K_s x - F_d}{m_p} \tag{7}$$

$$\frac{di}{dt} = \left(V - Ri - E(x,i) \cdot \frac{dx}{dt} \right) \cdot L(x,i)^{-1} \tag{8}$$

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

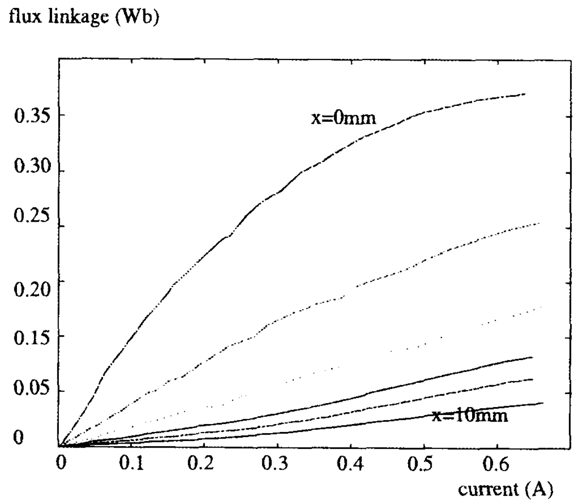

Figure 2 Flux linkage vs current at different positions

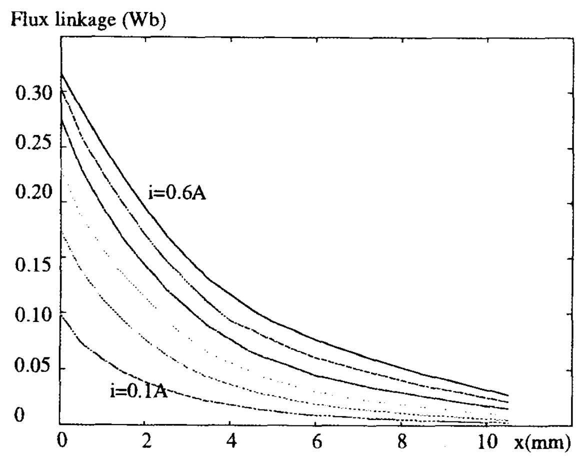

Figure 3 Flux linkage vs position at different currents

PROPORTIONAL CONTROL

There is little in recent literature which deals with control of linear solenoids. For the related problem of variable reluctance rotary machines, a number of linearisation techniques have been attempted. Illic'-Spong *et al.* [7] used feedback linearisation in a simulation study of the control for a variable reluctance motor. D.G. Taylor [8] proposed a reduced order composite control method for variable reluctance motors, but the method requires external analogue circuitry.

This paper proposes a dual rate cascade control, with a faster inner loop current controller and a slower PID outer loop trajectory controller. A non linear function is introduced to linearise the relation between force output of the position controller and the current setpoint to the current controller. The method is relatively simple and can be implemented in a fully digital form. A block diagram of the overall control system is shown in figure 4.

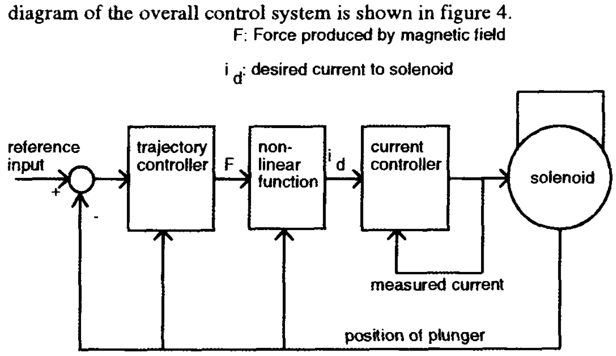

Figure 4 Block diagram of the control system

Exploiting the fact that the current loop dynamics are an order of magnitude faster than the mechanical dynamics, note that in Equation (8), *E(x,i)* and $\frac{dx}{dt}$ are effectively constant within the time scale of the current loop. *L(x,i)* can thus be simplified as *L(i)*. This implies that we need only the static function of Figure 2 to link the current and mechanical dynamics.

THE CURRENT CONTROLLER

A simple PI controller for the current loop is proposed in figure 5.

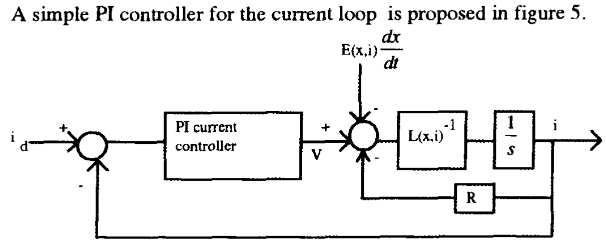

Figure 5 The current controller

Note that $E(x,i)\frac{dx}{dt}$ constitutes a disturbance term to the current loop which is approximately constant over the time scale of the current loop dynamics. Its effect on the current loop is compensated for by the integral action in the PI controller. Figure 2 shows that *L(i)* is approximately constant except at the end points of the solenoid travel. This allows us to design a current controller for a nominal linear system.

Note too that for the current controller to track its setpoint rapidly, it may be necessary to use high gain. To account for saturation, it is important that the PI controller used has anti reset windup features.

THE TRAJECTORY CONTROLLER

The position trajectory controller is a typical PID controller. This controller is designed on the assumption that the current controller has perfect tracking capability (ie. $i=i_d$) The mechanical dynamics are described by Equation (7).

For most practical applications, the plunger does not need to travel very fast. Together with the relatively slow dynamics, this implies that the trajectory controller has a much smaller bandwidth than the current controller.

In Figure 4, the nonlinear function between the trajectory controller output and the current controller setpoint is described by Equation (5) and Figure 3. It is evaluated at the same rate as the slow sub-system.

There are many ways to implement this nonlinear function.

1. By using an appropriate curve fitting technique to approximate with first, second or third order functions [3,4,5].
2. By using a two dimensional look up table in memory [9].
3. By implementing a neural network.

The first method uses the least memory, but involves complex calculations. The second method is the fastest, because it does not involve any online calculations. However, the memory requirement is very large, especially when high resolution is required. The last method is a very powerful option. Apart from mapping the force function, it can also be used to compensate flux leakage, hysteresis, and other nonlinearities in a magnetic circuit. However, the cost of hardware implementation is higher.

This paper uses a combination of the first and the second methods to realise the nonlinear function. A small look up table together with two dimensional linear interpolation is used.

IMPLEMENTATION

The proposed control scheme is implemented on an industrial switching solenoid with the following characteristics:

Type	Linear Travel Switching solenoid
Rated voltage input	24V
Maximum current	0.6A
Resistance R	40 ohms
Inductance L	100 - 250 mH
Plunger travel	10mm

Figure 6 shows the current experimental setup. A digital signal processor is used to implement all the control functions. The solenoid has a mechanical resonant frequency of about 800hz. To ensure that this resonant mode is *captured* by the position controller, a position controller sampling frequency of 2khz was selected. The current loop has a time constant of about 2.5ms (which is large compared to many rotary motors). This should allow current sampling frequencies of say 1khz. However in this set of experiments, to ensure that the current loop is significantly faster than the position loop, a sampling frequency of 10khz was used. The PWM driver has a chopping frequency of 25khz. Position is sensed with a linear variable differential transducer. ±65V is supplied to the PWM driver, which is 2.5 times the normal supply voltage of the solenoid. The higher voltage is used to obtain a larger dynamic range.

The cascade control arrangement described in this paper has separated the current nonlinearities from the mechanical dynamics, and the nonlinear function has compensates for the magnetic force nonlinearities.

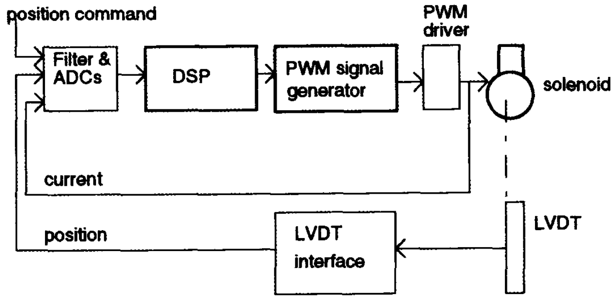

Figure 6 Setup of the control system

Other factors which will affect the practical implementation of the system also need to be considered. These are:

1. Hysteresis
2. Resolution of the look up table
3. Operation range limitations

Figure 7 shows the hysteresis loop characteristics of the solenoid at various plunger positions. The figure shows that hysteresis effect is largest when position=0. Such a large effect will produce a "latching function" on the motion of the plunger. When the plunger starts to move away from position=0, additional force is required to pull the plunger out. To avoid the hysteresis effect, it is best not to attempt proportional control within the 0-2mm travelling range.

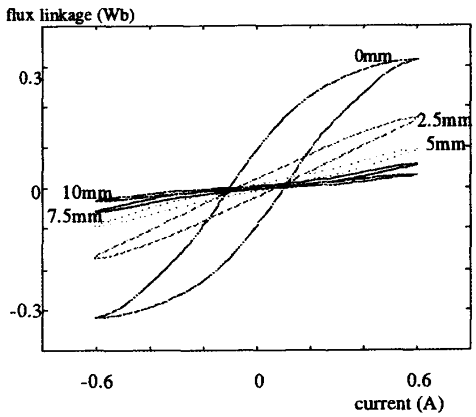

Figure 7 Hysteresis loops of the solenoid actuator

Another factor which influences the operation of the proportional solenoid is the resolution of nonlinear function. Higher resolution will lead to better accuracy. This paper uses a small look up table (20 x 20 elements) to store the nonlinear characteristics, and a two dimensional linear interpolation to find out the intermediate values. The size of the matrix is such that a 3% worst case deviation from the nonlinear function is maintained under linear interpolation. Figure 8 shows the resulting approximation.
Figure 8 is effectively a force profile of the solenoid at different current levels and positions. The top left hand corner is the

operating area with the highest force, while the bottom right hand corner is the operating area with the lowest force.

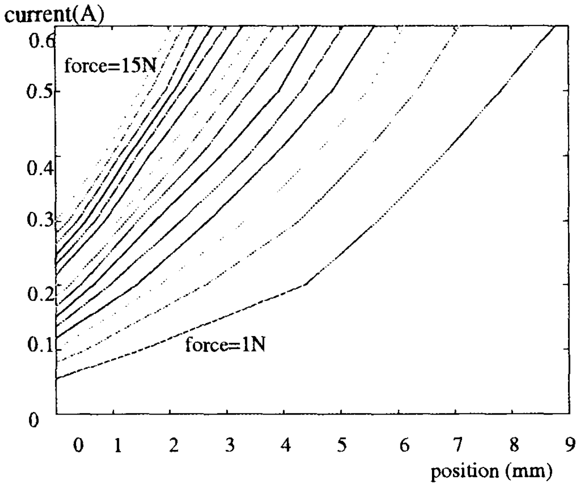

Figure 8 Current vs position at different force level

Figure 8 also illustrates the variation in system gain with operating point. At position=0, a slight variation in the current will cause a large variation in the force exerted on the plunger. On the other hand, when position=9mm, force exerted on the plunger can never be greater than 1N, even when maximum current is applied. Clearly, control at either end of the travel is difficult.

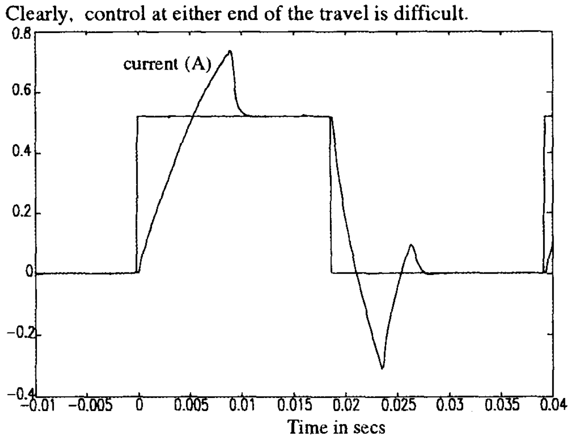

Figure 9 Current response to step setpoint change at x=10mm.

RESULTS

The PI controller for the current loop is tuned with the plunger locked at $x=0$. A Ziegler Nichols tuning procedure was adopted. The performance of the resulting inner current loop is shown in Figures 9 and 10 with the plunger locked in two extreme positions.

The two figures show that the worst case settling time is around 15*ms*. When the plunger is fully inserted (x = 0), the inductance of the solenoid is fairly large (≅250mH). Therefore the response of Figure 10 is slower than that of Figure 9, when the solenoid's inductance is much lower (≅100mH).

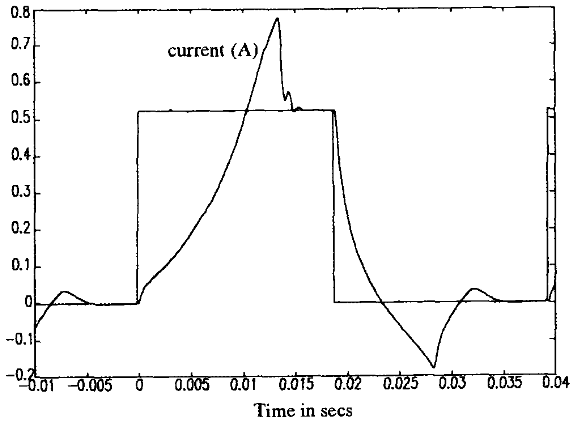

Figure 10 Current response to step setpoint change at x=0mm.

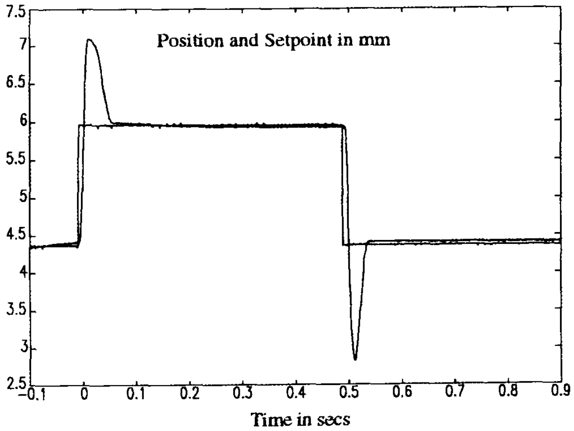

Fig 11a Step response with position controller

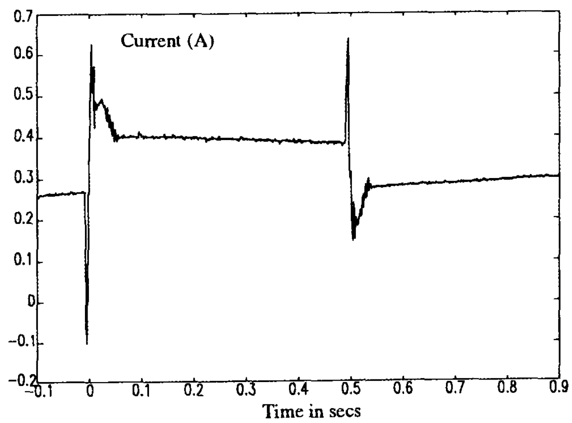

Fig 11b Current response with step change in position setpoint

A Ziegler Nichols tuning procedure was also adopted for the outer position controller. Figure 11a shows the response of position to a step change in setpoint while Fig 11b shows the corresponding current response.

The apparent reverse in current direction can be explained as follows. The change in the setpoint occurs over a change in mode of the spring, from compression to extension. An increase in current causes the plunger to retract, ie x decreases. As x gets smaller, less current is required to obtain the same force level. At the same time, the opposing force exerted by the spring increases. In figure 11b the initial current drop reduces the magnetic force, which allows the spring to push the plunger outwards. The position dependent gain is clearly illustrated here. The plunger is pushed forwards and overshoot occurs. This brings on an increase in current to force the plunger back to its desired position in a relatively sedate fashion. The current settles at i=0.4A which is a higher value corresponding the new plunger position x.

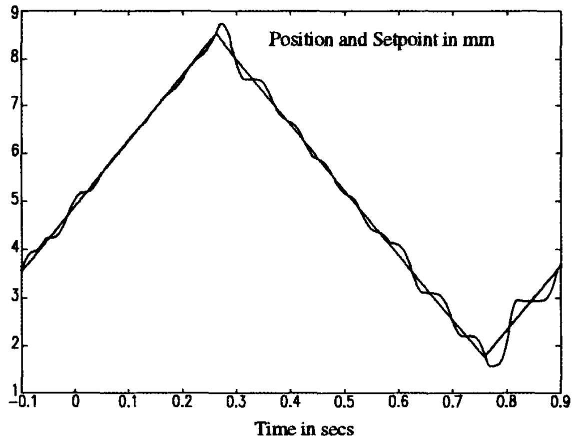

Figure 12a Triangular position trajectory response

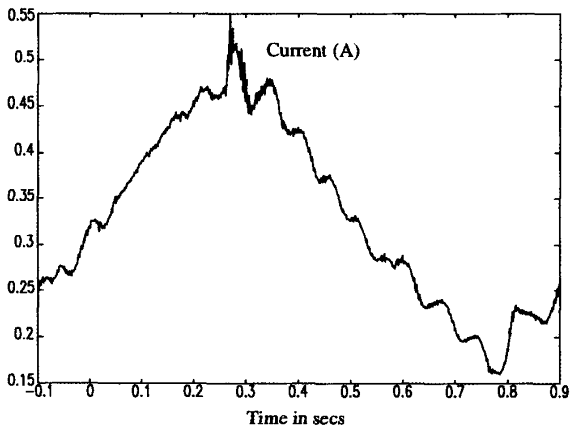

Figure 12b Current response with triangular position trajectory setpoint

Figure 12a shows the response of a triangular position trajectory command, while figure 12b is current response during this time. The figures illustrate reasonable tracking away from the end points. When the plunger goes to less than 2 mm, the hysteresis end effects clearly influence the controller response. Current waveform resembles a triangle waveform because force produced by the magnetic field is a function of x.

These plots show that the plunger can follow position trajectories reasonably within a wide operating range. This range and accuracy is adequate for many proportional solenoid applications.

Figure 13a and figure 13b show the position response and current response due to an upward load perturbation, and figure 14a and figure 14b show the position response and current response to a downward load perturbation. These perturbations are emulated by applying an impulse to the plunger. The figures show that the settling time is in the order of 0.12sec which is reasonable given the simple controllers used.

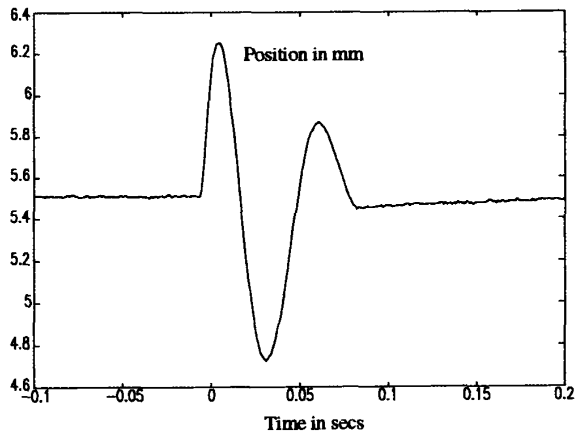

Figure 13a Position response due to upward load perturbation

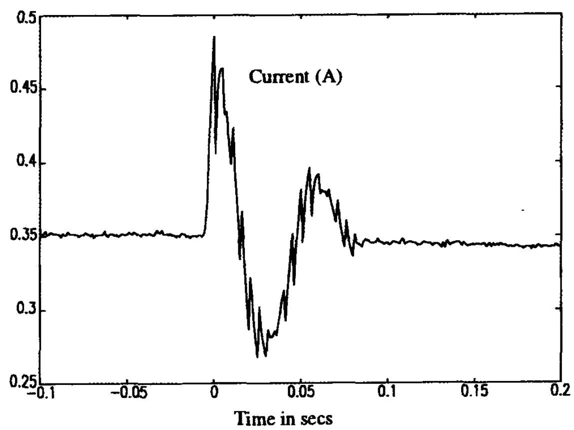

Figure 13b Current response during upward load perturbation

CONCLUSION

This paper proposes a method for converting normal switching solenoids to proportional actuators. To accomplish this goal, a simple control strategy for the nonlinear system is used. A dual rate cascade controller with an intermediate static nonlinear map is found to be adequate. The overall control system consists of a fast

PI current controller, a nonlinear map, and a slow PID trajectory controller.

Current related nonlinearities are attenuated by the fast, high gain current feedback loop. The nonlinear force-position and force-current relationships are inverse mapped with a piecewise linear function.

The method is implemented on a typical industrial solenoid valve. Though the experiments have been carried out with high performance processors, the use of simple linear controllers and a static nonlinear map suggest that a much simpler microcontroller or a low end digital signal processor would be adequate. The closed loop responses obtained also suggest that a greatly increased sampling period would be quite adequate.

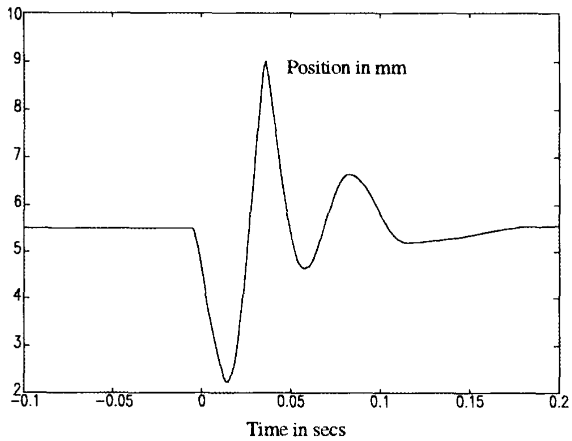

Figure 14a Position response due to downward load perturbation

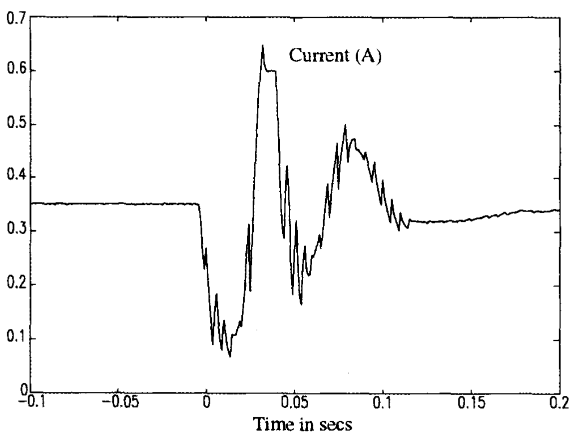

Figure 14b Current response during downward load perturbation

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