SIMULATION AND EXPERIMENTAL STUDIES TOWARDS THE DEVELOPMENT OF A PROPORTIONAL SOLENOID

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Abstract

This paper describes part of a project which aims to evaluate the feasibility of using a solenoid in force and position control. To obtain a control model, the dynamic behaviour of the solenoid is first simulated based on linear magnetic principles. However, results indicated that simulation using a simple form of magnetic circuit description is not accurate and requires improvement. To obtain a more accurate dynamic model, the flux linkage measurements are performed at different currents and positions, by using a.c. excitation and induced e.m.f. obtained from a search coil. The measured data is then used to build a control model which includes magnetic non linearity. The simulated results from the improved model are then compared with actual dynamic measurements of a solenoid.

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.

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

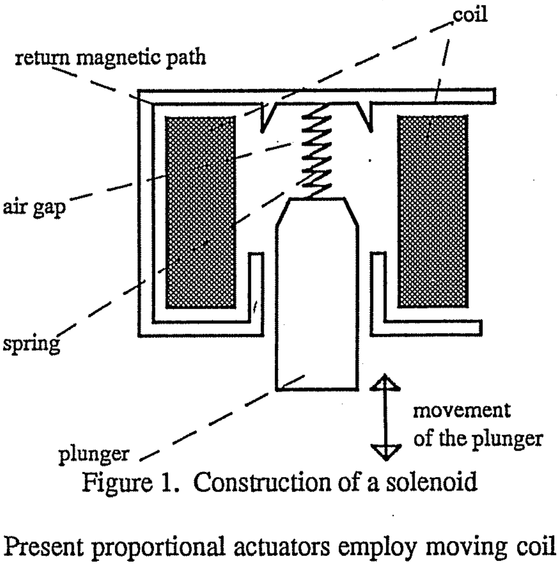

Figure 1. Construction of a solenoid

Present proportional actuators employ moving coil techniques working under constant magnetic field. This arrangement decouples the control from the nonlinear magnetic behaviour. On the other hand, solenoids are variable reluctance devices with their characteristics dictated by highly nonlinear magnetic circuit. Therefore it is very difficult to operate a solenoid as a proportional actuator using traditional feedback control techniques [1]. This paper examines the control characteristics of a solenoid and describes suitable techniques to construct a control model for the solenoid.

2. DYNAMIC SIMULATION BASED ON LINEAR MAGNETIC CIRCUIT

Before any form of control is implemented, the dynamic behaviour of the solenoid must be simulated and its control model developed.

Based on standard magnetic circuit principles [2], the inductance and force of the solenoid can be expressed as:

$$F(x,i) = \frac{\mu_0 N^2 A i^2}{x^2} \qquad (1)$$

$$L(x) = \frac{\mu_0 N^2 A}{\frac{l}{\mu_r} + x} \qquad (2)$$

where x is the plunger position, A is the effective cross sectional area, l is the effective return magnetic path, μ_0 and μ_r are permeability of free space and relative permeability respectively. The above equations assume that saturation does not occur; hysteresis and eddie current effects are also omitted. It assumes that the solenoid has a linear magnetic circuit.

The voltage equation is represented by:

$$V = \frac{d(L(x) \cdot i)}{dt} + Ri \qquad (3)$$

By referring to a free body diagram, the dynamic equation of a solenoid can be written as:

$$\ddot{x} = [F(x,i) - m_p g - k_s x] \cdot \frac{1}{m_p} \quad (4)$$

where k_s is the spring constant, m_p is the mass of the plunger, and g is the gravitational acceleration constant.

By using equations (1) to (4), dynamic simulation of a solenoid is done on a software simulation package SIMNON. The simulation package predicts the dynamic response of the plunger when a constant voltage source is applied to the solenoid.

3. SIMULATION RESULTS

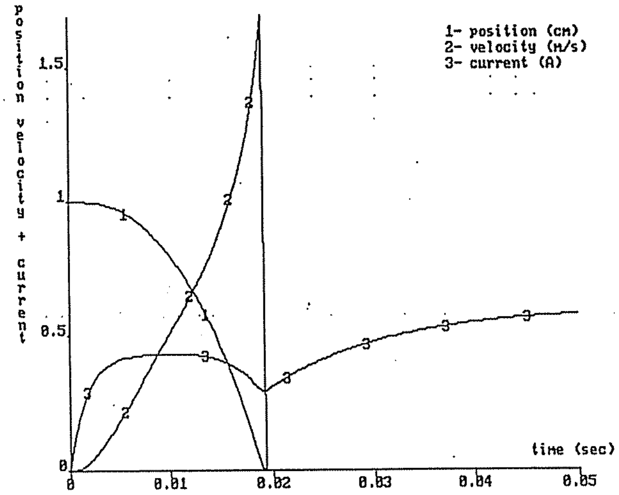

Figure 2. Simulated dynamic response of the solenoid

Three curves for position, velocity, and current are plotted in relation to time by the simulation package (see figure 2). The position and velocity curves show that the plunger moves with exponential speed and velocity. The velocity is at its maximum when it hits the end stopper. The simulation travel time is 18mS, which is much faster than the actual measured time of 32mS, as shown from the current curve in figure 3.

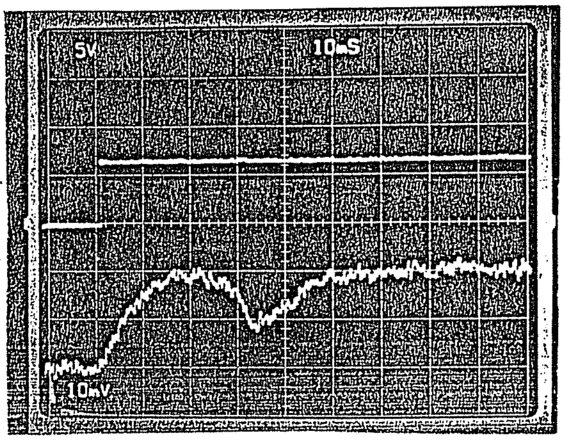

Figure 3. Measured current response of the solenoid

The previous simulation can only provide a rough estimation on the operation of a variable reluctance solenoid. It cannot give accurate results due to the presence of non linearity. The following components are non linear in a solenoid:

1. The flux linkage of the reluctance has a non linear relation with current. This means that the constant terms μ_r and L(x) cannot be treated as constants.
2. On top of the non linear relationship between flux linkage and current, there is another non linear relationship between flux linkage and air gap distance. In actual terms, there is a set of non linear curves between flux linkage and current, against various positions for a variable reluctance actuator.
3. Hysteresis and eddie current error has not been considered.

In order to obtain a more accurate dynamic model, the nonlinear characteristic of the variable reluctance actuator has to be investigated.

4. MEASUREMENT OF FLUX

Many methods are available on measuring the magnetic characteristics of switched reluctance motors [3] [4], 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. The plunger is also modified to accommodate a non ferric screw for accurate positioning during measurement.

To measure the induced flux, an a.c. voltage is fed into the solenoid coil, with the plunger fixed at a predetermined position. Voltage and current waveforms are digitised and recorded into the computer at 5khz per channel (100 sampling points per a.c. cycle). This procedure is repeated again with plunger positions incremented at 0.5mm interview. The whole process is completed until all the plunger positions' voltage and current waveforms have been measured. The measurement set up is shown in figure 4.

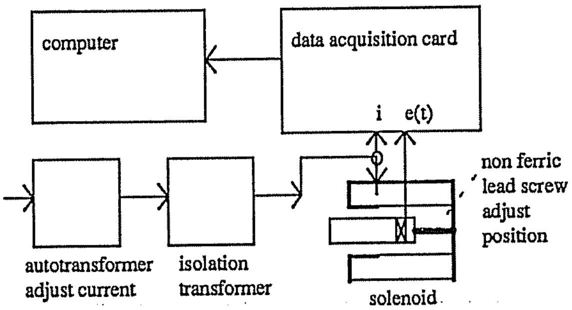

Figure 4. Measurement of magnetic characteristic

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

$$\Phi(t) = -\frac{1}{N_s}\int e(t)\cdot dt \qquad (5)$$

$$\lambda(t) = N\cdot\Phi(t) \qquad (6)$$

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.

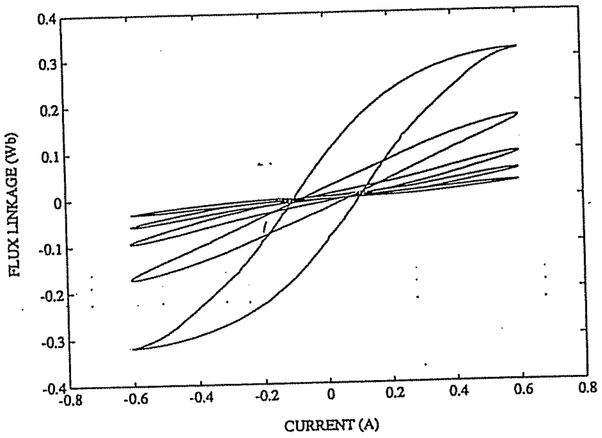

Figure 5. Hysteresis loops at different positions

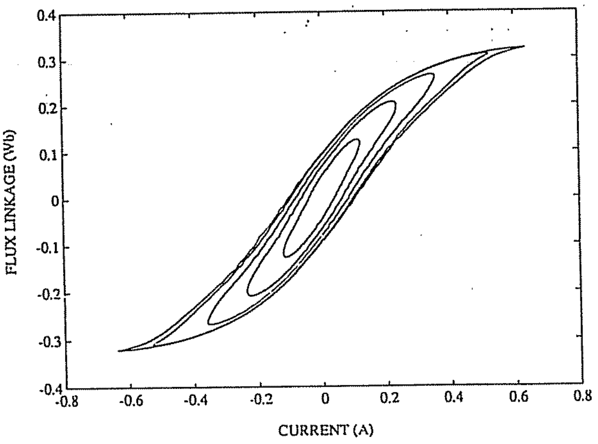

Figure 6. Hysteresis loops at different current levels

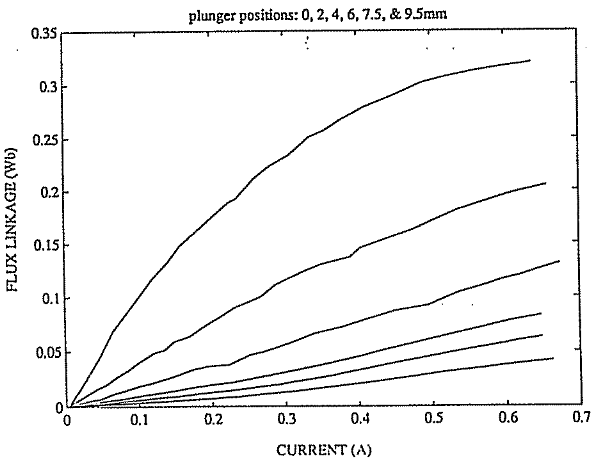

Figure 7. Flux linkage versus current

Figure 5 and 6 show the hysteresis loops at different plunger positions and currents levels, obtained from the measured data.

By joining the vertex of the hysteresis loops, the magnetic characteristics of flux linkage versus current at different positions (figure 7), and the flux linkage versus position at different current levels can be obtained (figure 8).

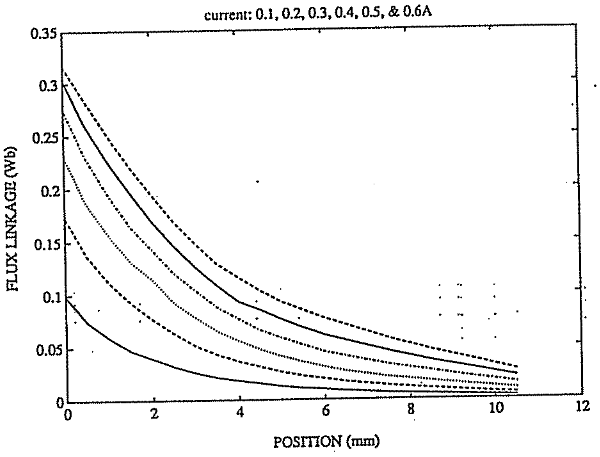

Figure 8 Flux linkage versus position

Once the flux linkage data is available, the force developed on the plunger can be found by calculating the rate of change of co-energy of the solenoid with position, by using the following formulae:

$$F(x,i) = \frac{\partial W'(x,i)}{\partial x} \tag{7}$$

$$W'(x,i) = \int_0^i \Phi(x,i) \cdot di \tag{8}$$

The static force from such a model is indicated in figure 9 for various solenoid currents and plunger positions.

5. Dynamic simulation using the non linear magnetic model

Once the non linear characteristics of the solenoid is obtained, the information is then used for simulation. The voltage equation of the solenoid is expressed as:

$$V = Ri + L_e \frac{di}{dt} + \frac{d\lambda}{dt} \tag{9}$$

where L_e is the inductance of the external circuit, R is the resistance of the solenoid, and V is the terminal voltage. Since flux linkage λ is a variable dependent on plunger position x, and current i, the equation can be rewritten as:

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

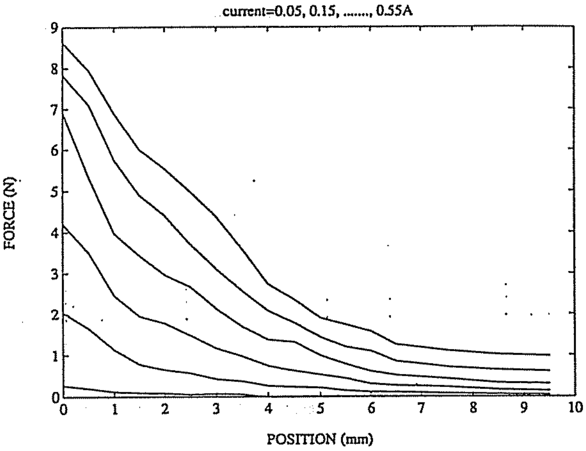

Figure 9 Force vs plunger positions

In the voltage equation, the first term is the resistive voltage drop, the second term is inductive voltage potential due to change of current, and the third term is the back e.m.f. coefficient. $\partial\lambda/\partial i$ and $\partial\lambda/\partial x$ are obtained from the magnetic characteristic measurements of the solenoid.

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

$$m_p \ddot{x} = F(x,i) - K_s x - m_p g - fr \tag{11}$$

F(x,i) is calculated from the non linear magnetic characteristics and fr is the frictional force acting on the plunger.

Using equations 10 and 11, and the non linear magnetic characteristic measurements, simulation on the dynamic response of the solenoid can be obtained. Figure 10 is the result of simulation. The predicted travel time of 29mS is much closer to the actual measurement than the earlier simulation on using a linear magnetic model. The predicted (figure 10) and actual response (figure 3) are now quite close.

6. Measuring the dynamic response of the solenoid

In order to verify the control model of the solenoid, position and velocity of the plunger must also be measured accurately. For this purpose, a fixture is built to accommodate the solenoid. Position and force sensors are employed for tracking the trajectory of the plunger and for measuring its static force. The overall set up is shown in figure 11.

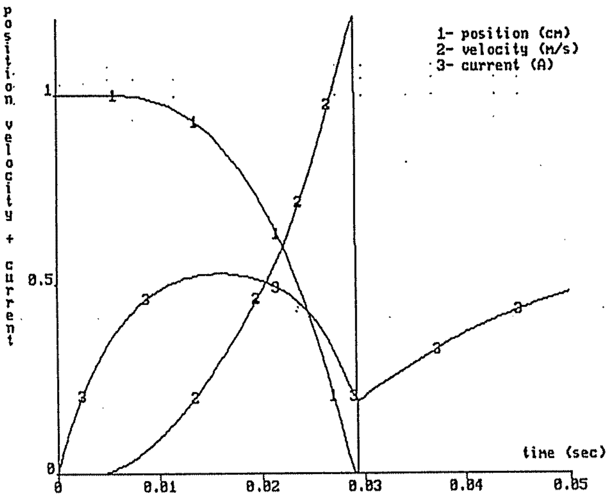

Figure 10. Simulated response of a solenoid

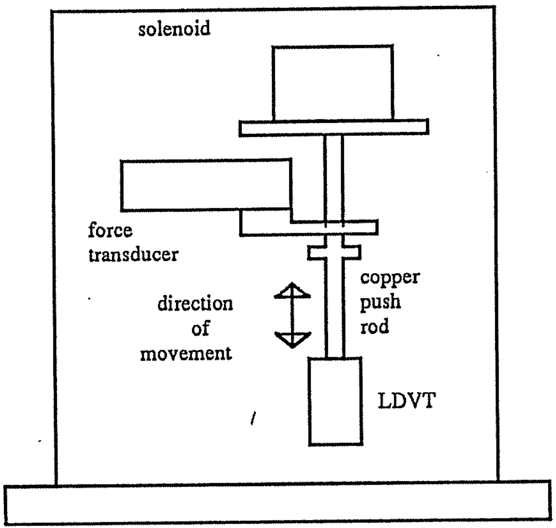

Figure 11. Fixture for measurement of dynamics

Figure 12 shows the measured switch on transient of a solenoid when it is activated by a constant voltage source. Since the plunger is now connected to a push rod, the travel time is much slower than before. In fact, the plunger will only start to travel when near maximum current (0.6A) is reached.

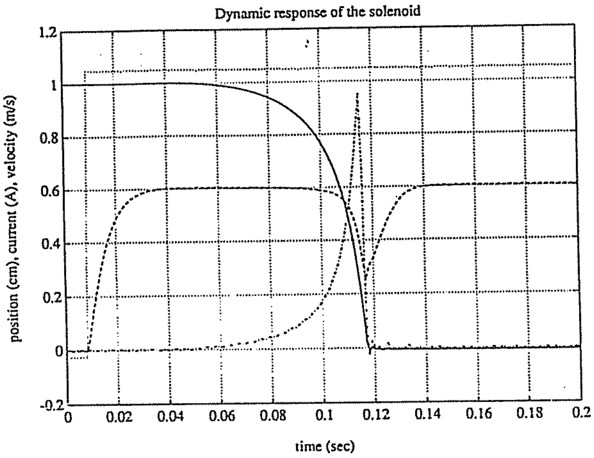

Figure 12. Actual measured dynamic response of the solenoid

To measure the frictional force of the moving component, the copper push rod is released from the higher end, and let it free fall to the lower end. During the free fall, its velocity is measured, and is shown in figure 13. The plot in figure 13 shows that the increase in velocity is quite linear, hence the deceleration due to frictional force is nearly constant.

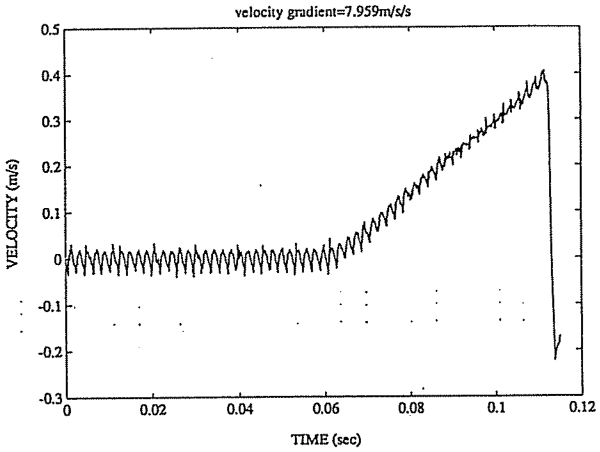

Figure 13. Velocity profile due to the free falling of the plunger and the push rod under gravity

7. RESULT OF SIMULATION ON THE OVERALL SYSTEM

Figure 14 shows the simulated result of the overall system. Position, velocity and current curves are approximately the same shape as the measured dynamic profiles. However, the predicted travel time of 69mS is much shorter then the measured travel time of 101mS. This is because of the inaccuracy involved when the solenoid is operating at its limit region. Due to the attachment of the push rod to the plunger, the moving part is much heavier than before. The moving part will only start to travel when peak current is reached. In this operating region, the simulation result is very sensitive to parameter variation, especially on force prediction. Therefore the simulation result is not as accurate as the previous case.

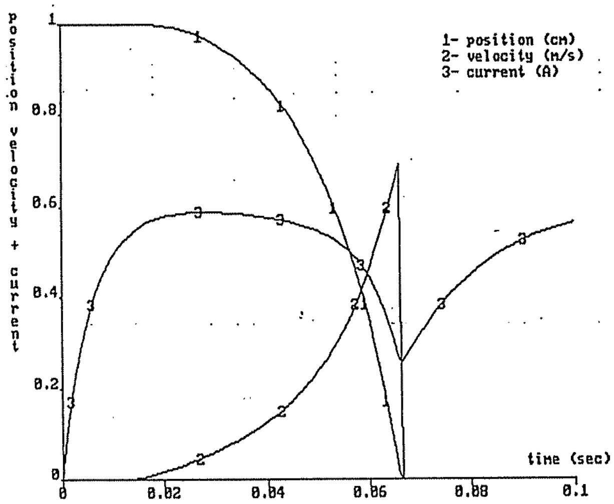

Figure 14. Simulated dynamic response of the whole system

Other factors, which have not been considered in the control model are the hysteresis and eddie current effects. However, in our case, these are not a major contributor to the inaccuracy of the simulation, because eddie current is insignificant when the velocity is low ; whereas hysteresis loss will be significant only when the air gap is small.

8. CONCLUSION

This paper has described some experimental and simulation studies towards the construction of a control model for a proportional solenoid. The early simulation indicates that control model based on linear magnetic characteristics will not provide accurate description on the solenoid's operation. The magnetic model must include magnetic saturation. To achieve this, measurements of flux linkage against position and current are taken. Based on the non linear magnetic characteristics, an improved control model is constructed. Dynamics of the solenoid is then simulated based on the improved control model. Result of simulation shows that the dynamic model is reasonably accurate under normal operating condition.

9. REFERENCES

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