ISSN 1726-5479

SENSORS & TRANSDUCERS

9 vol. 120 /10

TEDS Sensors, IEEE 1451 Standards

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 120, Issue 9,
September 2010

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
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Sensors & Transducers Journal

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Volume 120
Issue 9
September 2010

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 120, Issue 9, September 2010, pp. 142-151

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Performance Characterization of a Long-Stroke Direct-Drive Electromagnetic Linear Actuator

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Received: 8 August 2010 /Accepted: 14 September 2010 /Published: 27 September 2010

Abstract: This paper presents an analytical characterization for the dynamic performance of a direct drive linear actuator that works by current switching and modulation of an array of consecutive electromagnetic solenoids. The solenoids considered in this work have significant number of turns in both the radial direction and the axial direction. A mathematical model for the magnetic field density and the magnetic force acting on a magnetic dipole placed along the axis of the solenoids is developed. The effect of coil length, inner radius, outer radius and number of turns in the axial and radial directions on the force generated is investigated analytically. The analytical model was verified using Finite Element Method (FEM) simulation for a wide range of input current and geometry. The simulations show that the distribution of the magnetic field density and the magnetic force can be manipulated by changing radial span, or the number of radial turns of the solenoid's coil. It is shown that when the outer radius to length ratio exceeds 0.5, the solenoid force varies linearly with axial distance along the solenoid axis making it possible to generate a uniformly traveling magnetic field using a simple energization schemer for the solenoid coil set. *Copyright © 2010 IFSA.*

Keywords: Direct drive linear actuator, Magnetic field density, Magnetic force, Dynamic performance

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1. Introduction

Linear actuators are used to produce linear motion in various industrial application including packaging machines, machine tools, and other automated material handling equipment. Direct drive linear actuators or linear motors use electromagnetic solenoid coils to drive a magnetic plunger and can offer a number of advantages over conventional pneumatic or hydraulic actuators in terms of speed, accuracy, reliability, power consumption, environmental impact and cost [1]. These actuators, however, were restricted for use in short stroke, low force applications due to the limited force provided by conventional permanent magnet materials, and the non-linearity of the magnetic field and force acting on the plunger. Recent developments in the control technology, both in hardware and software and the availability of low cost high-strength permanent magnets made of neodymium-iron-boron NdFeB or samarium nickel SmNi allowed direct drive linear actuators to overcome these limitation. The utilization of such actuators is now being investigated in a variety of macroscale and microscale applications including linear micro motors [2, 3], pumps for biomedical applications [4], and magnetic resonance imaging (MRI) measurements [5-7].

A schematic illustration for a direct drive linear actuator is shown in Fig. 1. It consists of a set of solenoid coils wrapped around a straight hollow tube in which a permanent magnet plunger can slide. The solenoid coils are sequentially and independently energized using microprocessor control to create a traveling magnetic field which the permanent magnet plunger follows. Plunger motion is determined by magnetic field distribution along the actuator's axis, which, in turn, depends on the programmable energization scheme of the coils.

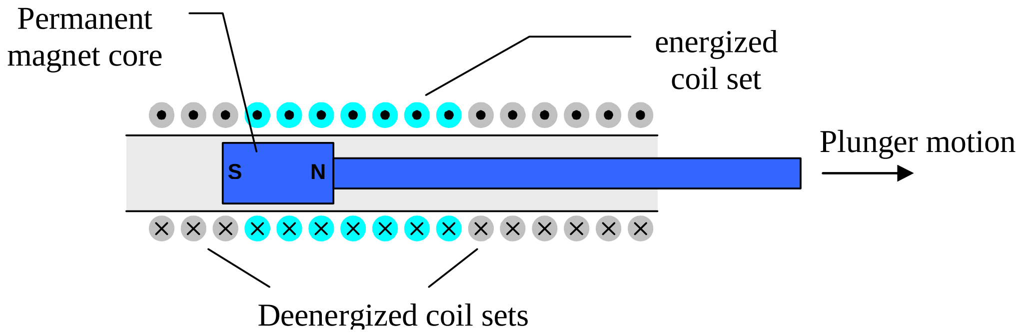


Fig. 1. Direct drive linear actuator concept.

A number of investigations have presented analytical treatment for the magnetic field and magnetic force of direct drive actuators. Mohan et al [8], for example, introduced a lumped-mass model for different shapes of spiral inductors such as square, hexagonal, and circular shapes. The models were based on empirical data only. Other like Chiou et al used numerical methods to study the microcoils parameters for optimization purposes [9]. The same numerical models were reported by Lin et al [10] where an identification of governing parameters such as coil diameters and number of turns had been laid out. A simpler methodology had been proposed by Gracia et al to model the magnetic field of microcoils. In this methodology the microcoil is divided into a number of straight segments with a finite length [11]. Beyzavi et al [12] reported an analytical model for planar coil developed and compared to experimental data, however this model assumed a small number of turns in the radial direction of the coil and thus does not account the effect of a significant number radial turns. Recently, a four-stage methodology was developed by Al-Sharif et al [13] for the modeling the axial force exerted by an electromagnet on a concentric permanent magnet. This methodology comprises modeling the permanent magnet as a current sheet based on the permanent magnet material and its dimensions and predicting the radial magnetic flux density from the electromagnet at any point off its axis. This is followed by calculating the axial force exerted by the electromagnet onto a concentric current carrying ring along its axis, and onto a number of contiguous rings that represent the model of the permanent magnet.

This work presents an analytical characterization for the dynamic performance of a direct drive linear actuator. A mathematical model for the magnetic force resulting from one energized solenoid coil on a magnetic dipole placed along the coil's axis is first developed. The effect of coil length, inner radius, outer radius and number of turns in the axial and radial directions on the force on the magnetic dipole was investigated. FEM simulations were carried out to verify the developed model. FEM simulations investigated the influence of the different coil parameters on the resultant magnetic field, and the resultant force. Good agreement has been achieved between the analytical model and FEM results over a wide range of coil parameters

Next, the effect of current switching and modulation of an array of consecutive electromagnetic solenoids using different energization schemes on the motion dynamics of a magnetic plunger placed along the actuator's axis was investigated. The magnetic plunger is modeled as a magnetic dipole. The analytical developed expressions for the force acting on the dipole were used to characterize the quasistatic and dynamic response of the plunger.

The coils considered in this study have significant number of turns in both the radial and the axial directions. It is shown that a coil with a significant number of turns in its radial direction produces a force curve which varies linearly with distance over the coil's length. This makes it possible to generate a uniformly traveling magnetic field using a simple energization scheme.

2. Analytical Model

Consider a solenoid coil with length l, inner radius r_1 and outer radius r_2 as shown in Fig. 2. As mentioned above, we consider a coil with a significant number of turns in both the axial and radial directions, and we let N_a and N_r denote the number of turns in those directions respectively. If the coil's axis is along the x axis., a section through the coil parallel to the $y-z$ plane produces a linear "Archimedean" spiral as shown in Fig. 3. The equation of the spiral's centerline may be expressed in polar coordinates by:

$$r = r_1 + K\theta\ ,\ 0 \leq K \leq 2\pi N_r \tag{1}$$

The parameter K is the polar slope (change in r per θ) of the spiral. Using (1), K is given by:

$$K = (r_2 - r_1)/2\pi N_r \tag{2}$$

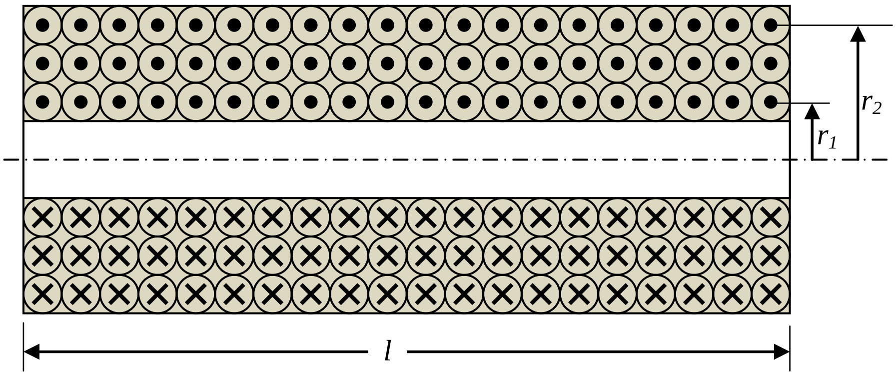


Fig. 2. Solenoid coil dimensions used in the analytical derivation.

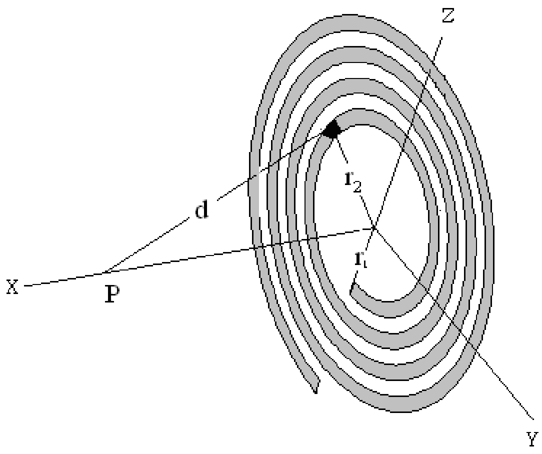


Fig. 3. Spiral section in the coil in the y-z plane.

To develop a formula for the magnetic field density along the coil's axis, we start with the simpler case of a coil having its wires wrapped at a constant radius from its centerline. This coil will have a few number of turns in the radial direction and is treated extensively in classical electrodynamics. The inner radius of the coil is assumed to be equal to its outer radius, and is denoted by the radius r. We further assume a length l, current I and number of axial turns in the axial direction N_a. This. The x component of the magnetic field along the solenoid's centerline B_x is given by [14]:

$$B_x = \frac{\mu_0 N_a I}{2l}\left[\frac{x}{\sqrt{x^2+r^2}} + \frac{l-x}{\sqrt{(l-x)^2+r^2}}\right], \tag{3}$$

where $\mu_o$is the magnetic permeability of free space. Utilizing (2), the magnetic field strength for a differential segment with an included angle $d\theta$ is found by multiplying the right hand side in the expression above by $d\theta / 2\pi$ to obtain:

$$dB_x = \frac{\mu_0 N_a I}{4\pi l}\left[\frac{x}{\sqrt{x^2+r^2}} + \frac{l-x}{\sqrt{(l-x)^2+r^2}}\right] d\theta \tag{4}$$

Substituting for $d\theta$ from (1) we obtain:

$$dB_x = \frac{\mu_0 N_a N_r I}{2l(r_2-r_1)}\left[\frac{x}{\sqrt{x^2+r^2}} + \frac{l-x}{\sqrt{(l-x)^2+r^2}}\right] dr \tag{5}$$

Noting that the product $N_a N_r$ in (5) is simply the total number of turns in the coil N. The equation may be integrated between r_1 and r_2 to obtain:

$$B_x = \frac{\mu_0 N I}{2l(r_2-r_1)}\left[x \ln\left(\frac{r_2+\sqrt{x^2+r_2^2}}{r_1+\sqrt{x^2+r_1^2}}\right)\right] + \left[(l-x)\ \ln\left(\frac{r_2+\sqrt{(l-x)^2+r_2^2}}{r_1+\sqrt{(l-x)^2+r_1^2}}\right)\right] \tag{6}$$

The resultant magnetic force F acting on a magnetic dipole $\mu = \mu_x i$ placed along the axis of the solenoid is related to magnetic field by:

$$F = \nabla(\mu.B) = \nabla(\mu_x B_x) = \mu_x \frac{dB_x}{dx} i \tag{7}$$

and the x component of the magnetic force is found with reference to (6) to be:

$$F_x = \frac{\mu_0 \mu_x NI}{2l(r_2 - r_1)} \left[\begin{array}{c} -\ln\left(\frac{r_2 + \sqrt{x^2 + r_2^2}}{r_1 + \sqrt{x^2 + r_1^2}}\right) - \frac{1}{x^2}\left(\frac{r_2}{\sqrt{x^2 + r_2^2}} - \frac{r_1}{\sqrt{x^2 + r_1^2}}\right) \\ + \ln\left(\frac{r_2 + \sqrt{(l-x)^2 + r_2^2}}{r_1 + \sqrt{(l-x)^2 + r_1^2}}\right) + \frac{1}{(l-x)^2}\left(\frac{r_2}{\sqrt{(l-x)^2 + r_2^2}} - \frac{r_1}{\sqrt{(l-x)^2 + r_1^2}}\right) \end{array} \right] \tag{8}$$

Finite element simulations were used to verify the expressions developed. The Finite Element Method Magnetics (FEMM) package [15] was used to obtain the magnetic filed density along solenoid axis. We use the values of coil geometry and current shown in table 1 in the FEMM model. Fig. 4 shows the magnetic field distribution along coil axis resulting from the analytical solution and from the FEMM simulations. Very good agreement is obtained. for a different or a wide range of input current.

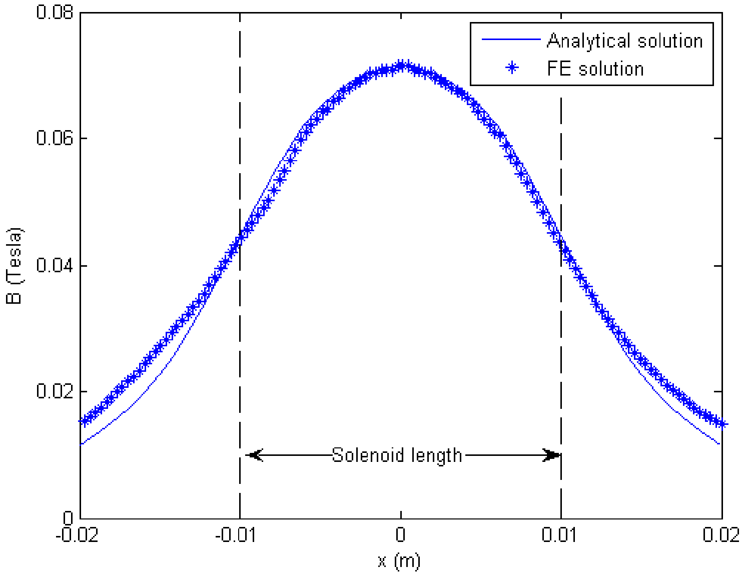


Fig. 4. Magnetic field density distribution along the coil axis: analytical and finite element.

3. Quasistatic Performance

The quasistatic performance of the actuator describes the motion of its plunger under zero load and no dynamic or inertia effect. In quasistatic mode, the equilibrium position of the magnetic plunger is the location of the maximum field density curve of the combined field density of the energized coils To study the quasistatic performance of the actuator, we use a simple coil energization scheme in which three consecutive coils are simultaneously activated and de-activated to create a uniformly traveling magnetic field. The scheme uses a Rise-On-Fall current signal where three consecutive coils from the coil set are activated during the time period. If the activated coils are labeled *A*, *B* and *C*, coil currents, I_A, I_B and I_C during a time period t. are given by:

$$
\begin{aligned}
I_A &= I_{max}(1-t)\\
I_B &= I_{max}(1-t)\\
I_C &= I_{max}t
\end{aligned}
\qquad (10)
$$

The current profile is illustrated in Fig. 5 for a coil set consisting of eight coils. The scheme may be implemented using an analog microcontroller output with the needed power amplification hardware, or more simply, using a pulse width modulated output. In either case, we are interested in the shape of the resulting magnetic field profile as it travels along the solenoid axis. Fig. 6 shows typical magnetic field density distribution curves for six time frames during an energization interval of one second. The location of the maximum field density in each curve is of interest as it represents the steady state location of a magnetic plunger operating in quasistatic mode. Fig. 7 shows the location of this point as a function of time for four different values of coil radius ratios. Fig. 7 also shows the effect of inner radius ratio on plunger motion for actuators energized with the rise-on-fall energization scheme with $r_2/l = 1$. The figure shows that a uniform, jerk-less motion is obtained when $r_1/l = 0.8$.

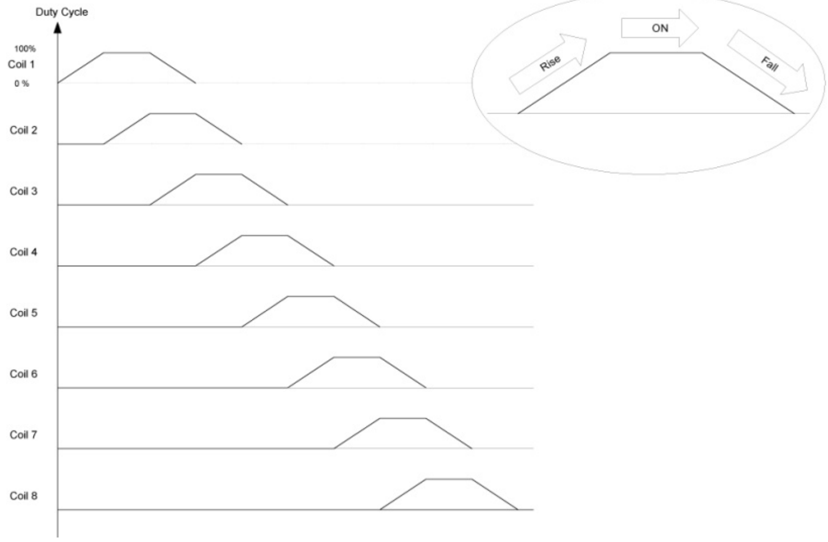


Fig. 5. Coil energization pattern for eight coils according to the rise-on-fall scheme.

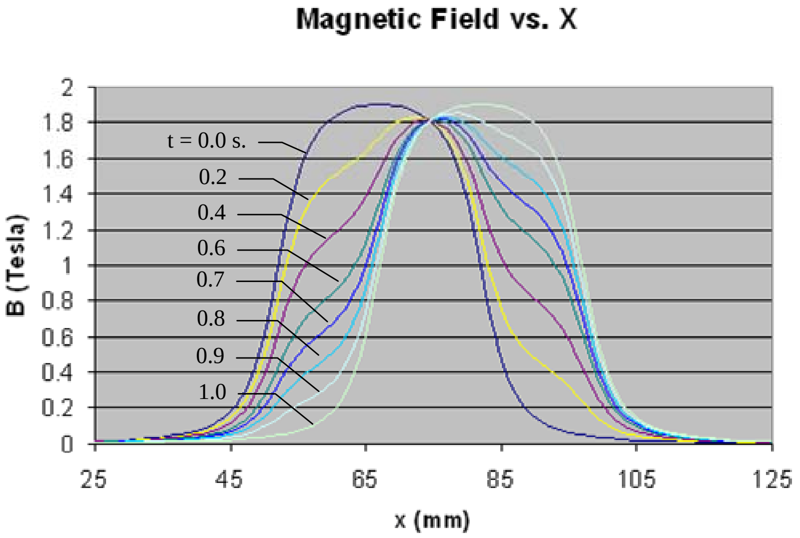
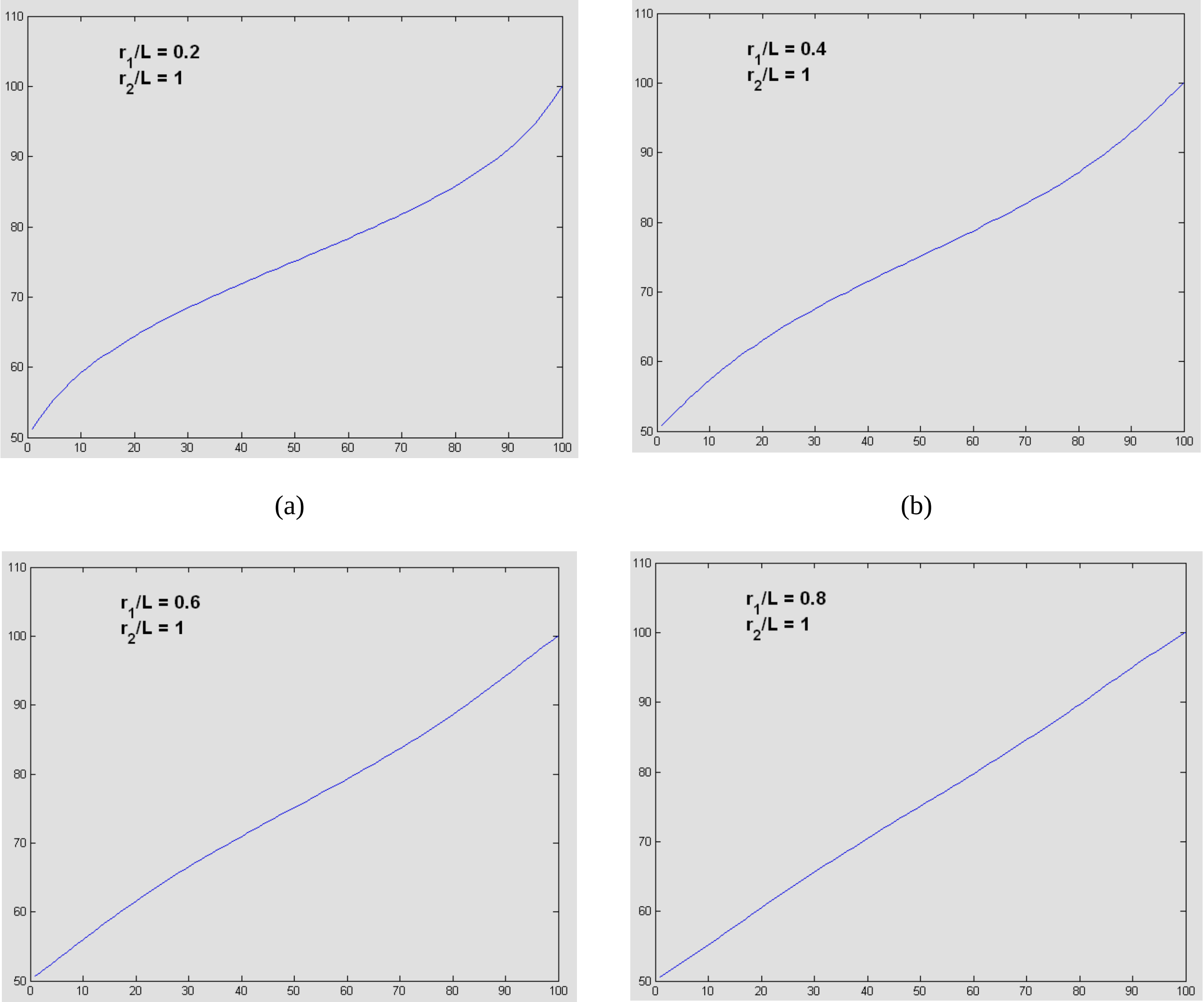


Fig. 6. Distribution of magnetic field density with time under the rise-on-fall scheme.



(a) (b)

(c) (d)

Fig. 7 Effect of inner radius ratio on plunger motion under the rise-on-fall scheme: (a) $r_1/l = 0.2$ $r_2/l = 1$; (b) $r_1/l = 0.4$, $r_2/l = 1$; (c) $r_1/l = 0.6$, $r_2/l = 1$ and (d) $r_1/l = 0.8$, $r_2/l = 1$.

The motion shown in Fig. 8 describes an experimental no-load plunger motion obtained for coils with $r_1/l = 0.4$ $r_2/l = 1$ using the energization pattern described in (9). The experimental motion is a repeated pattern of the motion predicted using the simulations of Fig. 7.

4. Discussion

To further illustrate the effect of the various geometric parameters of the coil, we now study the effects of coil geometry in terms of nondimensional parameters. The plots in Fig. 9 and Fig. 10 show, respectively, the effects of outer radius ratio, r_2/l and inner radius ratio r_1/l on the force acting on a magnetic dipole placed along the axis of the coil.

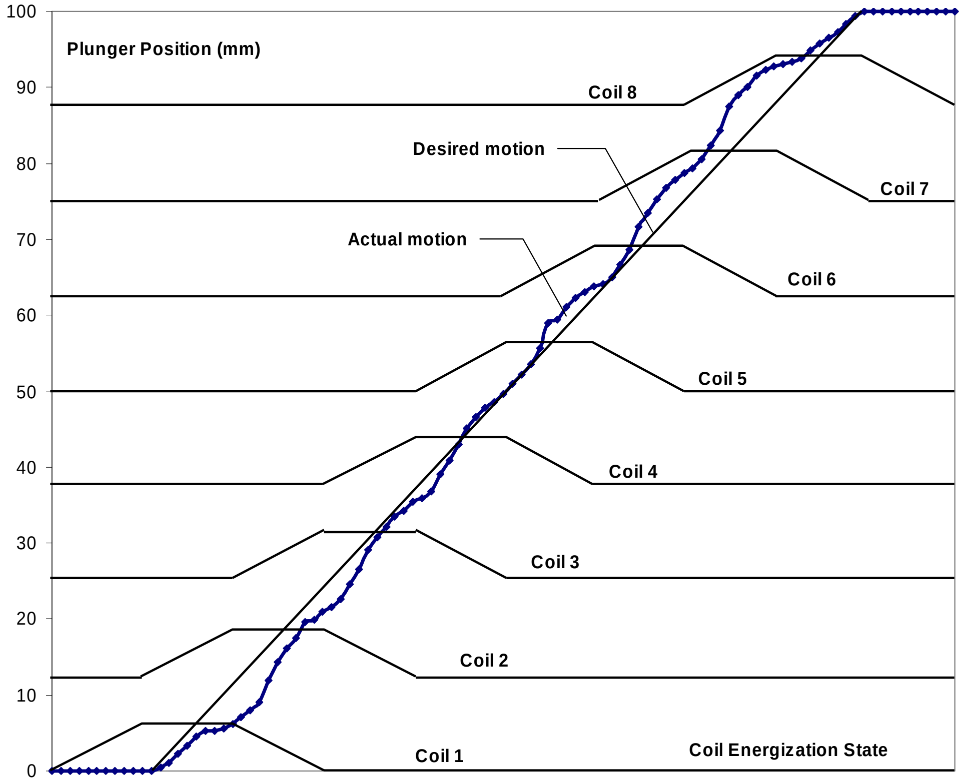


Fig. 8. Coil energization and experimental plunger position with time.

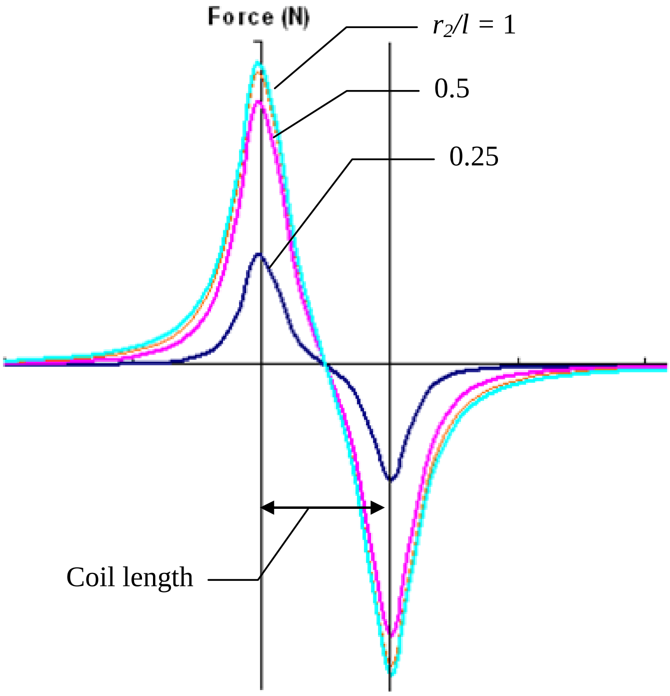


Fig. 9. Effect of outer radius ratio on the force acting on magnetic dipole.

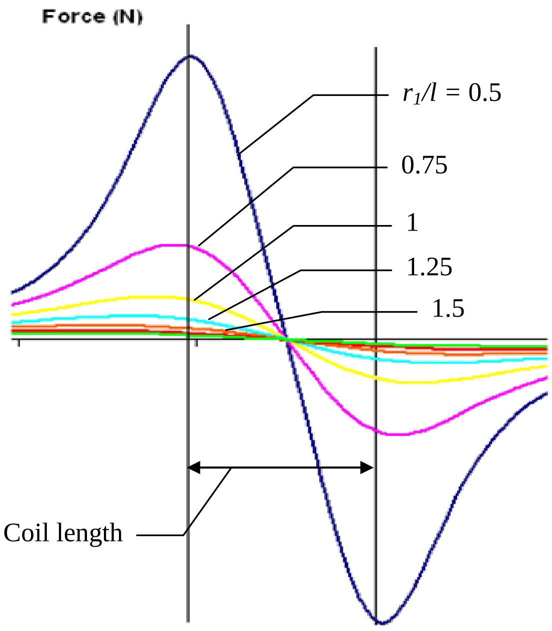


Fig. 10. Effect of inner radius ratio on the force acting on magnetic dipole.

Fig. 9 and Fig. 10 show that the force acting on the magnetic dipole assumes its maximum value when the dipole is at either end of the coil, and it becomes zero at the midpoint of the coil's centerline. The figures also show that small values of radial ratios cause the force curve to become nonlinear with distance. Small radial ratios cause the force curve to become flat close to zero over the solenoid length. This nonlinear trend results in actuation and control difficulties in the long stroke linear actuator, as it will be difficult to generate a uniformly traveling magnetic field using a simple coil energization algorithm. For $r_2/l > 0.5$ the force behaves almost linearly with axial distance while being zero at the midpoint of the centerline. The linear trend makes it possible to generate a uniformly traveling magnetic field using a set of solenoid coils in order to drive a magnetic plunger. Energizing one of the coils at the end of a set of consecutive solenoid coils while simultaneously de-energizing a coil on the opposite end of the set has the effect of shifting force curve by a distance equal to the coil length. A linear trend ensures that a significant amount of force is generated overcome the inertia and frictional forces which the actuator is to overcome.

5. Conclusions

This work presents the basic analytical characterization for the dynamic performance of a direct drive linear actuator. An analytical model for the magnetic field and the magnetic force acting on a magnetic dipole placed along the axis of one of the solenoid coils of the actuator was developed. The model takes into consideration the effect of coil length, inner radius, outer radius and number of turns in both the radial and axial directions. The model was tested for different sizes of microsolenoid and shows a good agreement with Finite Element Method (FEM) simulation for a wide range of input current and geometry.

The simulation shows that the distribution of the magnetic field density and the magnetic force can be manipulated by changing the inner radius, the outer radius of the spiral coil and the polar slope of the spiral coil. For an outer radius to length ratio exceeding 0.5, the solenoid force varies linearly with axial distance along the solenoid axis. This was utilized to generate a uniformly traveling magnetic field using a simple energization schemer for the solenoid coil set, which results in a uniform, jerk-less quasistatic performance of the actuator's plunger.

Acknowledgements

The author acknowledges the support of the Deanship of Academic Research in the University of Jordan and the Deanship of Scientific Research in King Faisal University in this work.

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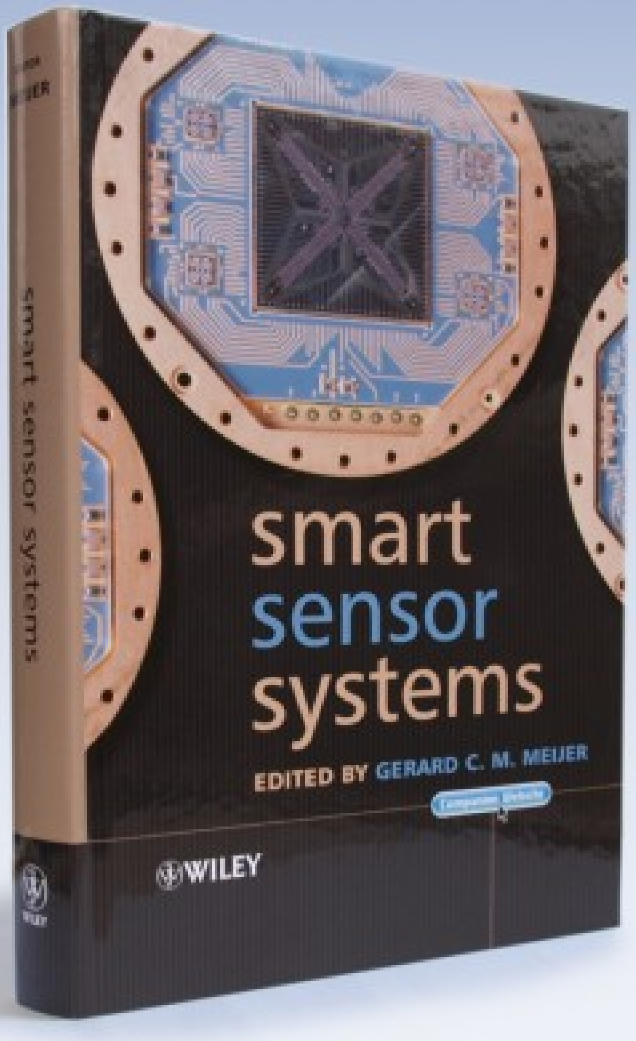
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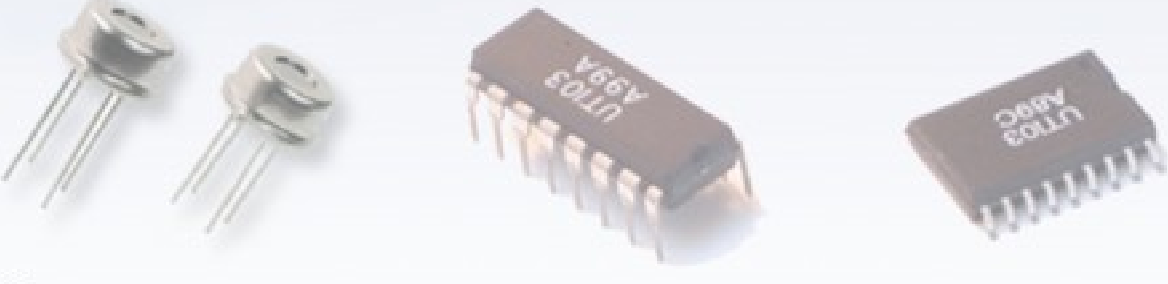
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