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An Approach for Electromagnetic Linear Propulsion

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Abstract:This article presents a review of Electromagnetic linear propulsion in the aspects of construction, features, electromagnetic modelling, simulation, analysis and design. A particular emphasis is presented on the design and performance analysis of electromagnetic accelerator for the sliding applications in specific domains.
Keywords:Flux distribution, permeance, inductance profile, Electromagnetic propulsion , Sliding control.

I. INTRODUCTION

In the world of automation, vast applications are visible for linear motion. In which one of the application which are used in our daily life is sliding application like Sliding door, Sliding windows, Sluicing gates etc. The sliding applications contain a motor and activation system to operate them. An automatic sliding application is commonly found in industries, offices, airports and shop entrances. Till today the linear motion is created using the conventional electric motors which has many limitations like efficiency, complex construction and multiple operations. This article presentslinear motion applicationsusing the Electromagnetic propulsion system.

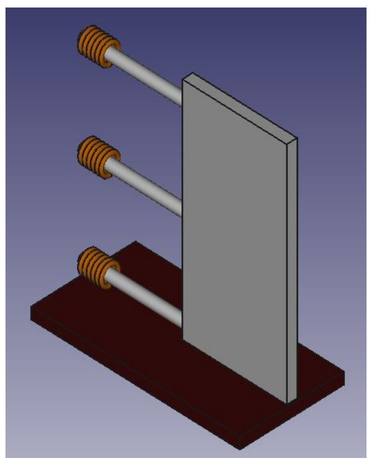

Fig. 1.3D structure of the proposed design

This Electromagnetic propulsion system consists of one coil, known as a drive coil which accelerates a moving part known as a plunger. A series of current pulse is applied to accelerate the plunger to which the sliding object is attached. A schematic of proposed system is shown in Fig.1. The moving part is initially positioned at a distance ‘x’ away from the centre of the drive coil. When the drive coil is energized, a transient magnetic field is build that creates a force on the movable part, drawing it to the centre of the coil. The inductance of the system will change, as the moving part moves. It achieves a maximum inductance when the centre of the moving part coincides with the centre of the drive coil. However, the coil driven system has a disadvantage that once the accelerated object moves past the point of maximum inductance, the net restoring force acts to return the object back. This effect is named as `suck-back'. This action is undesirable as it is opposing the desired direction of motion of the object and it reduces the resultant muzzle velocity of the moving plunger from the accelerator system.

AymenLachheb*et al* developed a model of a linear switched reluctance motor which can be used for sliding door applications with open loop and closed loop controls in [1]. Their study focused on LSRM modelling neglecting end effect and assuming the inductance and force have a sinusoidal form. Ali Mosallanejad, Abbas Shoulaie*et al* derived an equation for change in inductance in a tubular linear reluctance motor during its operation for the linear movement of the plunger based on energy method in [2]. Field

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intensity inside the core is considered but the flux deviations or the flux leakages at the entry and exit ends were not considered. A three-phase slot less tubular permanent-magnet actuator is selected for accelerating 20g mass in a pick and pack application in [3]. The stator contains coils and the translator is a moving-magnet where the force is calculated using the Lorentz force equation. The earlier references [4-8] mainly focused on the design and performance of electromagnetic propulsion systems with limitations such as: each of the drive coil length equal to projectile lengths, neglecting the flux distributions, infinite permeability of the core materials. The control of the propelling object was not discussed in any of the past literatures.

As the magnetic flux plays an important role in generating the thrust in an electromagnetic propulsion system, each and every flux region is taken into account. This article mainly highlights the inductance profile equation derived from the flux distribution including entry and exit leakages. The above mentioned limitations from the past literature are restrained. A novel control technique is proposed to switch the coil in the sequence based on the requirement of opening and closing of the sliding objects. With the help of polarity switching, the object can also be moved forward and backward at required speed. When compared with previous studies, the proposed coil driven system can provide a much better output performance and control with a low cost.

II. SYSTEM PARAMETERS

The total design of the electromagnetic accelerator is based on the inner diameter (D_i) and outer diameters (D_o) of the drive coil.

$$D_i = f(D_p, g) \quad (1)$$

$$D_o = D_i + f(D_w, A_w, layers) \quad (2)$$

Where 'A_w' is area of cross section of conducting wire, '*layers*' indicate the number of layers wound on the drive coil, 'D_i' inner diameter of the drive coil, 'D_o' outer diameter of the drive coil, 'D_w' diameter of wire.

To analyse the accelerating force and velocity, the inductance gradient at every displacement position is to be calculated. Firstly the electrical parameters of the accelerating system are derived from

$$R_{coil} = f(l_w, A_w, \rho_w) \quad (3)$$

$$l_w = f(l_c, d_i, d_o, N) \quad (4)$$

$$[L(x)^-, L(x)^+] = f(l_c, l_p, N, x, \mu_r) \quad (5)$$

Where 'R_{coil}' is the drive coil resistance, $L(x)^-$ & $L(x)^+$ are the minimum and maximum inductances,'x' is the displacement of the object, 'l_p isthelength ofplunger rod.

The accelerating force and exit velocity are estimated from the following equations:

$$F = f\left(I, \frac{dL(x)}{dx}\right) \quad (6)$$

$$a = f(F, M_p) \quad (7)$$

$$v = f(a, t) \quad (8)$$

III. CHARACTERISTIC ANALYSIS

The Electromagnetic accelerator has very high nonlinear magnetization characteristics, so the magnetic circuit analysis is used to obtain the nonlinear magnetization data, to estimate the flux linkages.

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A. Inductance Characteristics

According to the system parameters, the intensity of the magnetic field will depend on the inductance profile. The inductance offered by the drive coil is minimum when the moving plunger is at the entrance of the drive coil; inductance slowly reaches its maximum value when the plunger completely fills the coil. The inductance formula based on the position of the moving part is derived using Magnetic Potential Method. Figure 2 presents the flux lines in the drive coil using a FEMM software tool. The inductance characteristics are obtained using the Simulink model in MATLAB based on the position of the moving part.

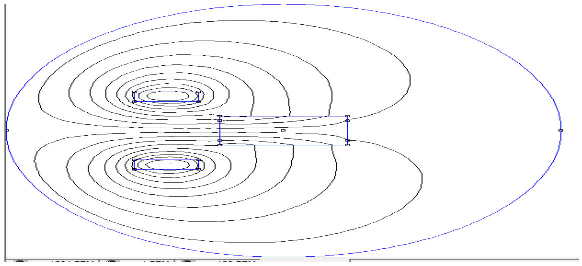

Fig.2. Flux lines in the coil using FEMM software

Permeance in Flux path 1,

$$P_1 = 0.318\,\mu_0\,d \qquad (9)$$

Permeance Flux path 2 ,

$$P_2 = \frac{\mu_0\, h_m d}{\pi\,(h_m + l_g)} \qquad (10)$$

Permeance in moving part i.e. in path 3 and 4 are

$$P_3 = P_4 = \frac{\mu_0 \mu_r d}{2x} \qquad (11)$$

Permeance in Flux path 5,

$$P_5 = \frac{\mu_0 h_p d}{2(l_m - x)} \qquad (12)$$

Permeance in Flux path 6,

$$P_6 = \frac{\mu_0 (h_m + h_p \frac{d}{2})}{2\pi(\frac{h_m}{2} + h_p + l_g)} \qquad (13)$$

Permeance in Flux path 7,

$$P_7 = \frac{\mu_0 \mu_r h_m d}{l_m} \qquad (14)$$

Where 'h_m' is the height of metallic sheet covering the drive coil,'h_p' is the thickness of moving plunger, 'l_m' the length of metallic sheet, 'd' depth of metallic sheet of drive coil, 'μ_r' is the permeability of plunger material, 'l_g' is air-gap length.

Finally, the total reluctance 'R_{total}' offered by the magnetic field in the accelerating system with the moving plunger positioned at a distance 'x' from the entrance of the coil is

$$R_{total} = \frac{1}{P_1} + \frac{1}{P_2} + \frac{1}{P_3} + \frac{1}{P_4} + \frac{1}{P_5} + \frac{1}{P_6} + \frac{1}{P_7} \qquad (15)$$

The inductance of the coil using Magnetic Potential Method is

$$L(x) = \frac{N^2}{R_{total}} \qquad (16)$$

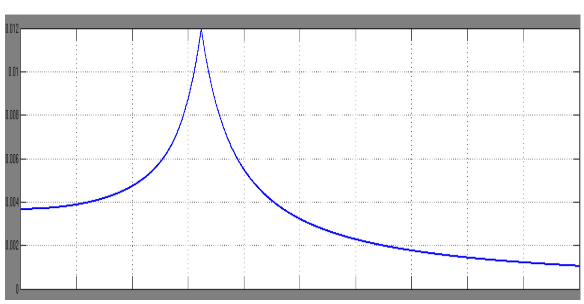

Fig.3. Inductance profile in Simulink model in MATLAB

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B. Output Thrust Characteristics

From the reluctance principle, the thrust will depend on the current and inductance. According to the above analysis, the inductance changes rapidly from the plunger starting position of the coil to the centre of the coil. Therefore, the output thrust will get its peak value at the centre of the coil as shown in fig 4.

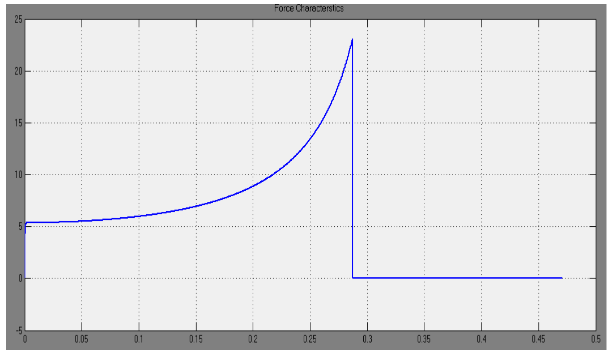

Fig.4. Thrust profile in Simulink model in MATLAB

C. Performance Analysis

The performance of any propulsion system can be analysed by the force generated and the velocity with which the object is accelerated. From the mathematical expressions it is evident that the drive coil current will affect the velocity of the moving object. With the simulation study it is observed that change in input supply to the drive coil alters the current in the system resulting in an improved velocity. Similarly, time to accelerate an object can be minimized by increasing the excitation to the drive coil. The effect of change in supply voltage on the velocity and time of acceleration of the object are shown in figures 5&6.

Table 1: Input Parameters of each Coil

Parameter	Values	Units
Voltage ,V	100	volts
Number of turns ,N	500	-
Coil length , lc	0.06	m
Air gap Length	0.003	m
Diameter of the Conducting Wire	0.61	mm
Permeability of Moving rod	5000	
Radius of the Coil	0.0535	m
Diameter of Moving Rod	0.1	m

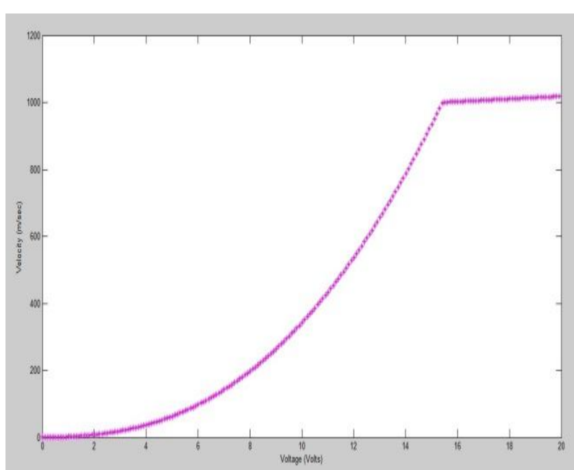

Fig.5. Effect of Voltage on Velocity

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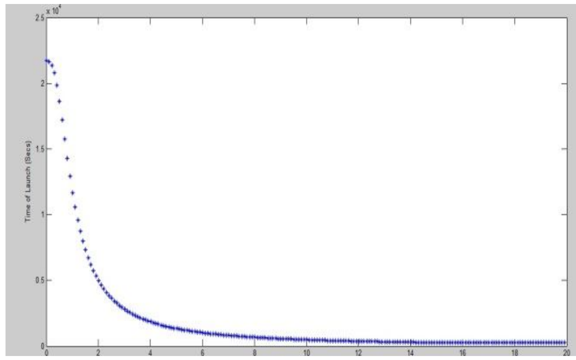

Fig.6. Effect of change in voltage on accelerating time of the object

IV. CONTROL SCHEME

The control scheme for the drive system is shown in fig 7. The model is built based on the electrical equivalent of the electromagnetic propulsion system [10&11]. A position sensor is used to detect the position of moving plunger inside the coil. Based on the position of the moving plunger the voltage is controlled with allowable current. A mathematical model of a single stage electromagnetic accelerator is shown in fig.8, built from the equations derived in section II&III.Fig.9 gives a comparison for change in velocity of the system with different number of turns in the coils. The characteristic clearly shows that by decreasing the number of coil, the plunger will have more velocity. This is mainly due to the variation of current with change in resistance of the coil with variable turns.

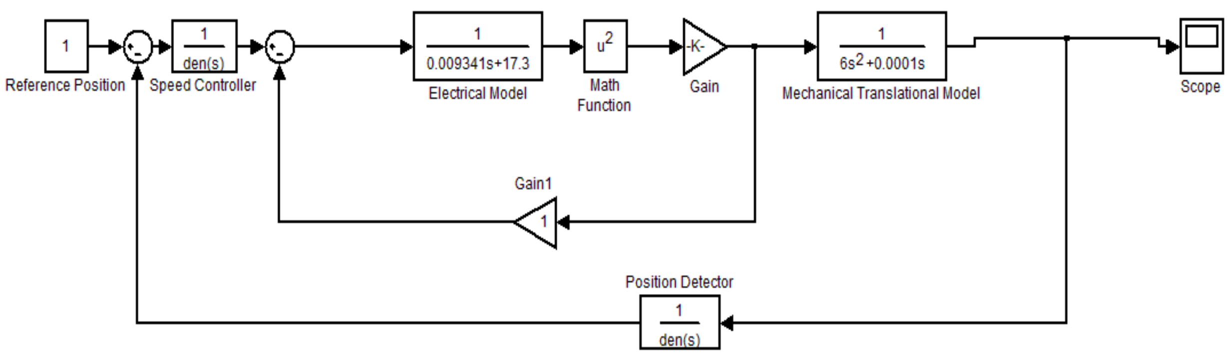

Fig. 7. Control scheme in MATLAB Simulink

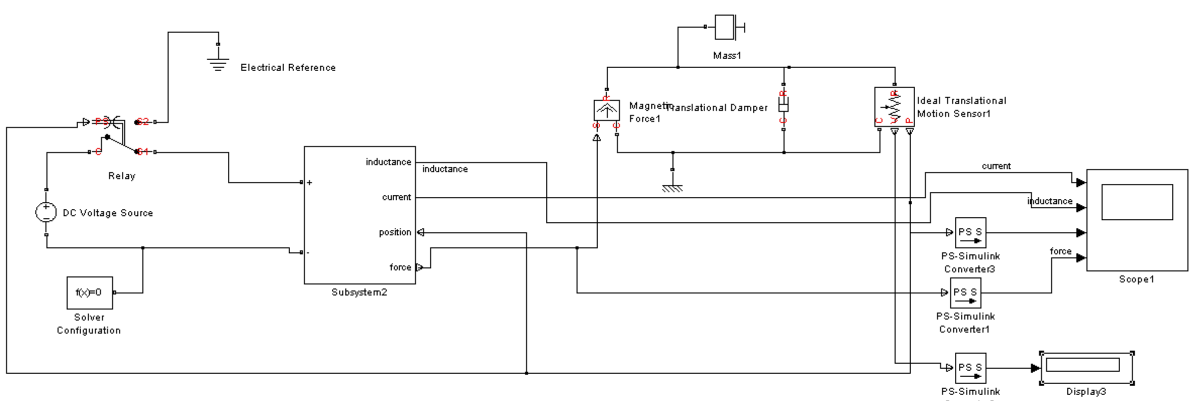

Fig.8. Building block of single stage electromagnetic accelerator in MATLAB Simscape

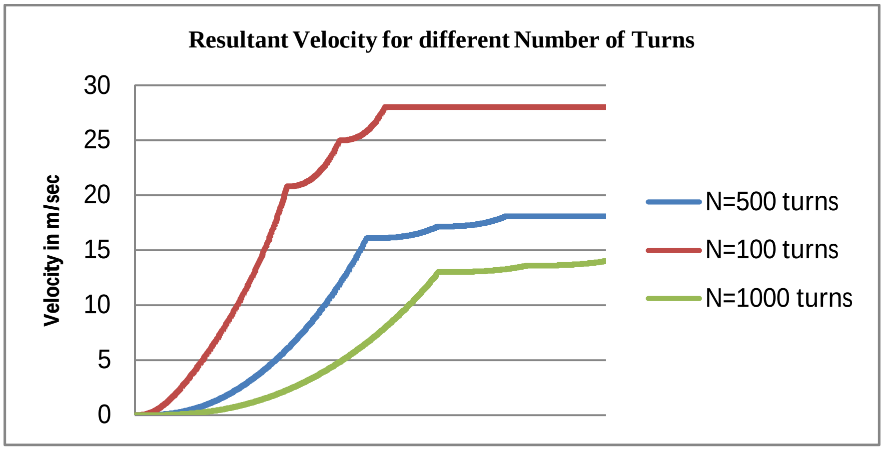

Fig.9 .Resultant Velocity with different coil turns

V. CONCLUSION

In this article, a particular emphasis is made on the design, control and performance analysis of electromagnetic linear propulsion system for the sliding applications. This design of the electromagnetic propulsion offers an advantage of overcoming the limitations observed in old literature by considering the leakage flux distributions in the system, reducing the size of the speed control driving equipment making the concept particularly suitable for the sliding applications. Simulation and performance analysis implemented to verify the proposed method making it much more effective and suitable for low speed and high thrust applications.

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