



## Dynamic modeling of direct drive axial flux PMLOM using FEM analysis

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### ABSTRACT

A general framework for the development of a new generation of PM Linear Oscillating Machine (PMLOM) using FE magnetic analysis suitable for short strokes is described in this paper. A microcontroller based IGBT inverter is developed for the control of thrust and oscillation frequency. The PMLOM can perform precision oscillation task with relatively low power dissipation. The use of powerful permanent magnet material such as Neodymium-Iron-Boron alloys has greatly improved the performance of the machine. The forces for aluminium mover embedded with rare earth permanent magnets are determined analytically and the results are validated extensively by comparison with finite element analyses.

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### Introduction

Linear motors are finding increasing applications in different specific areas like high-speed transport, electric hammers, looms, reciprocating pumps, heart pumps etc. [1],[2],[4],[6]-[8] and [9]. They are also well suited for manufacturing automation applications. Therefore, design of energy efficient and high force to weight ratio motors and its performance assessment has become a research topic for quite a few years. PMLOMs are one of the derivatives of the linear motors in the low power applications having the advantages of higher efficiency and high force to weight ratio. They can be supplied with dc or ac voltages [1],[2],[4] and [9] of which, the dc motors are having better efficiency due to the absence of core losses. The motor designed in this paper finds the suitability of application in the loads having low frequency and short stroke length. One such application is the heart pump, where frequency of oscillation is to be adjusted between 0.5 to 1.5 Hz, with the requirement of variable thrust depending on the condition of the heart under treatment. For analysis of such motors the main task is to determine the essential equivalent circuit parameters, which are its resistances and inductances. The resistances, for the machine, though vary with operating conditions due to temperature, do not affect much on its performance assessment. However, the inductances for these machines are mover position dependent and mostly affect the machine performance. Therefore, determination of these parameters is essentially required for analyzing the machine model. There are several works e.g. [3],[4] which assumes the machine inductance to be constant for simplicity of the model although different other works e.g. [1], [2],[5] and [12] dynamically estimate the inductance through FEM and field analysis for getting correct results. In [10] a low power tubular linear motor is developed for space usage where an equivalent circuit model is developed for the machine to analyze its characteristics. In [11] the development of Linear Switched Reluctance Motor (SRM) is

realized with higher primary poles which can result in complex switching topology for speed control. In [12] FEM based analysis and estimation of parameters are shown for a SRM.

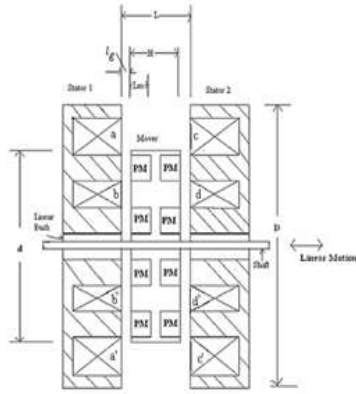
In this paper, the linear machine designed is having permanent magnet in the mover so that the force to weight ratio is improved. The machine under consideration is an axial flux machine and the mover is having a non-magnetic structure, which is aluminium. Also the rare earth permanent magnets used in the mover are having a relative permeability nearly equal to unity and therefore the magnetic circuit under consideration will be unsaturated due to major presence of air in the flux path. Hence, consideration of constant inductance is quite errorless for such kind of machines, which also conforms to the experimental data shown in this paper. Finally the machine is analyzed with the help of the field equations and solved for forces and resultant flux densities through FEMLAB6.0 and Mathworks7.0 and backed by suitable experimental results. The control circuit is simple which uses PIC16F877A microcontroller with switching between four coils and no closed loop position control is necessary for speed and thrust control. The proposed motor concept is validated through proper simulation and suitable experiments.

### Machine Construction

The construction of the prototype PMLOM is shown in Fig.1. Also the dimensional details of the motor are shown in Fig.2.



**Figure 1: PMLOM Construction (i) Stators with linear bearings to be mounted on both sides of the mover (ii) The Mover (iii) The PMLOM machine**



**Figure 2: Dimensional details of the developed PMLOM**

There are two concentric coils for each of the stators. They are connected in such polarities that the fluxes for both the coils aid each other to form the poles in the iron parts. The formation of the N and the S poles of the electromagnet of the stator are shown in the Fig.2.

The mover consists of aluminium structure embedded with rare earth permanent magnets with the polarities as shown. The force developed will be attractive on one side and simultaneously repulsive on the other side. These two forces act in the same direction to enhance the total force on the mover, assisting the linear oscillation of the mover cyclically.

#### Force Model

##### Poisson's Equation

The classical description of static magnetic fields are provided by Maxwell's equations

$$\nabla \times H = J \quad (1)$$

$$\nabla \cdot B = 0 \quad (2)$$

Where  $H$  is magnetic field intensity,  $B$  is magnetic flux density and  $J$  is the current density in the conductors producing magnetic field. The relationship between  $B$  and  $H$  can be written as,

$$B = \mu H \quad (3)$$

Where  $\mu$  denotes material permeability. Boundary conditions that must be satisfied at the interface between two materials having finite conductivities are,

$$\hat{n} \times (H_1 - H_2) = 0 \quad (4)$$

$$\hat{n} \cdot (B_1 - B_2) = 0 \quad (5)$$

where  $n$  is a unit vector normal to the boundary surface directed from region 2 to region 1. Since the divergence of the curl of any vector must always be zero, it follows from (2) that there exists a so-called magnetic vector potential  $A$  such that,

$$B = \nabla \times A \quad (6)$$

From (1) and (3),

$$\nabla \times B = \mu J \quad (7)$$

From (6) and (7),

$$\nabla \times (\nabla \times A) = \mu J$$

$$\text{Or, } \nabla (\nabla \cdot A) - \nabla^2 A = \mu J \quad (8)$$

For a DC situation or for a very low frequency variation of  $J$  which is 0.5 to 5 Hz in the present case, the term  $\nabla \cdot A = 0$ . This situation when considered in equation (8) results in,

$$\nabla^2 A = -\mu J \quad (9)$$

Equation (9) is the *Poisson's equation*. from which the magnetic vector potential  $A$  can be numerically calculated knowing the current density  $J$ . Having known  $A$  at different points the flux density  $B$  can be found out from (6).

##### Lorentz Force

The force exerted by a PM-sourced static magnetic field with flux density  $B$  on conductors carrying current with density  $J$  is known as the so-called *Lorentz force* and is given by,

$$F = \int_v (J \times B) dv \quad (10)$$

Now, if current is Z-directed and motion is X-directed, (10) can be written as,

$$F = - \int_v J_z B_y dv \quad (11)$$

Thus, for N-turn coil with z-direction length  $L$  of carrying current  $I$ , (11) can be written as,

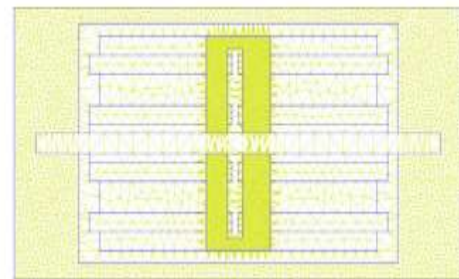
$$F = -NILB_{avg} \quad (12)$$

Where,  $B_{avg}$  is the average airgap flux density, which can be calculated from (6) considering machine geometry.

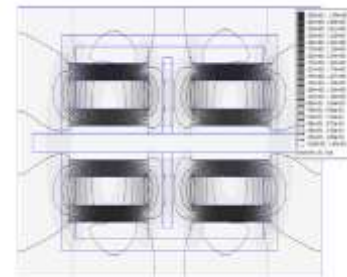
##### Simulation and Experimental Result

The proposed scheme is simulated under FEMLAB6.0 with Mathworks environment, which provides a finite element analysis. The machine specification used for both simulation and experiment is given in Table- 1

Figure 3(a), shows the FEM mesh configuration for the PMLOM Prototype while mover is oscillating at the centre, 5 Hz, 2.5A. Figure 3(b) shows the magnetic flux plotting of PMLOM while mover is oscillating at the centre of both stators at 5 Hz, 3.5A. Fig.3(c) shows the magnetic flux plotting of PMLOM while mover is oscillating near stator 2 at 1 Hz, 0.75 A. Fig. 3(d) shows magnetic flux plotting of PMLOM while mover is oscillating near stator 1 at 5 Hz, 3.5A. In Fig. 3(e) the magnetic flux plotting of PMLOM while mover is oscillating near stator 2 at 5 Hz 3.5 A and  $F= 15.5$  N is shown.



**Fig. 3(a) Finite element mesh of PMLOM while mover is oscillating at the centre, 5 Hz, 2.5A**



**Fig. 3(b). Magnetic flux plotting of PMLOM while mover is oscillating at the centre of both stators at 5 Hz, 3.5A**

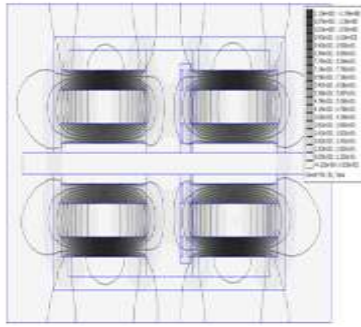


Fig.3(c) Magnetic flux plotting of PMLOM while mover is oscillating near stator 2 at 1 Hz, 0.75 A

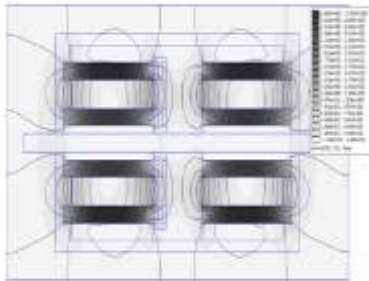
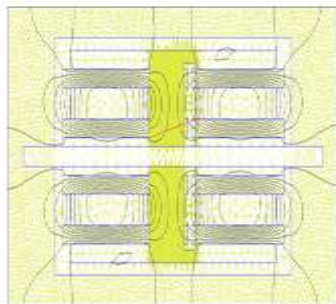


Fig. 3(d) Magnetic flux plotting of PMLOM while mover is oscillating near stator 1 at 5 Hz, 3.5A



For the FEM modeling calculations, material linearity of the NdFeB permanent magnet ( $\mu_r = 1.048$ ) was used. Its coercive force was assumed to be  $H_c = 925$  KA/m and the magnetization vector direction were adopted for the calculations. Very small air gaps compared with the main motor dimensions between permanent magnets and ferromagnetic rings were neglected due to very small magnetic permeability of the permanent magnets, which is acceptable.

In order to predict the integral parameters of the PMLOM, it is necessary to analyze the magnetic field distribution in the stator and mover. Obviously, it is possible to optimize the construction by making changes in the stator and mover geometries. The improvements of the structure result from knowledge of the magnetic field distribution. The presented results have been obtained for one variant of the motor construction.

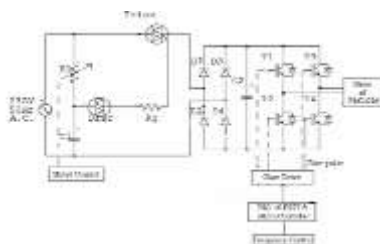


Fig. 4 Power & Control Circuit of PMLOM

The control block diagram along with the experimental set-up power electronic control circuit is shown in Fig.4. For this machine as the thrust force is proportional to the current hence the thrust control can be provided with variation of coil current. As the magnetic circuit is unsaturated the coil current is proportional to the input voltage. Then the thrust control is provided with the help of phase controlled ac supply which can vary the input voltage. The frequency control is provided with the help of a low cost and commercially available microcontroller PIC16F877A. The microcontroller is programmed to vary the frequency with the input reference voltage by changing its output pulsewidth. These pulses are fed to the IGBT through suitable drivers and isolators.

The control is reliable and provides a scope for portability to any remote place. The loading arrangement is provided with a mass and a pulley arrangement with a constant inductance L the response of a coil is

$$i(t) = \frac{V}{R} \left( 1 - e^{-Rt/L} \right) + I_0 e^{-Rt/L} \quad (13)$$

Where  $I_0$  is the initial current, which is  $-V/R$  in the present case. R is the total equivalent resistance and L is the total equivalent inductance of the coils looking from the source end. The equivalent circuit is shown in Fig. 5.

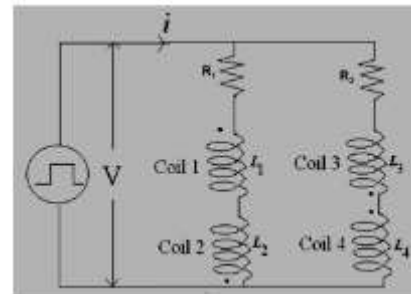


Fig. 5 PMLOM equivalent Circuit

Assuming  $R_{eqv} = R_1 = R_2$  (14)

The total equivalent resistance,

$$R = \frac{R_{eqv}}{2} \quad (15)$$

Equivalent inductance  $L = \frac{(L_1 + L_2) + (L_3 + L_4)}{2}$  (16)

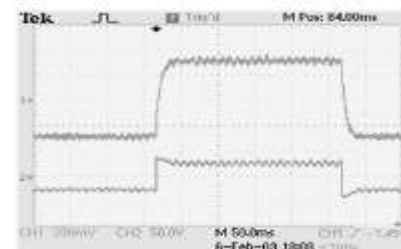
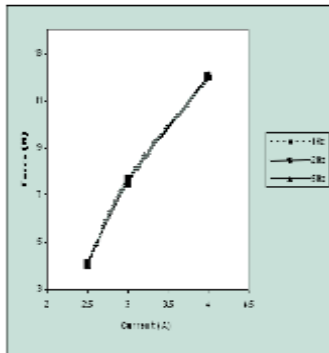
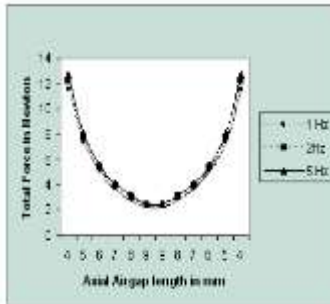


Fig. 6 Current and Voltage waveform of PMLOM

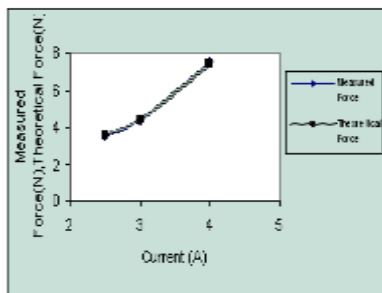
Fig. 6 shows the plot of the input Current and voltage waveforms of the machine at 5 Hz at full load. The current plot is seen to be exponentially rising and falling with the reversal of the input voltage. Also it becomes steady before the mover has reached its final end position. Thus the assumption of constant inductance for the machine is validated. Fig. 7 shows the variation of measured thrust force at varying currents. It is evident from this experiment that the motor thrust practically shows no change with



**Fig. 7 Measured Force versus Coil Current Characteristics**



**Fig. 8 Total Force versus Axial Airgap Length characteristics**



**Fig. 9 Comparison of measured Force versus Theoretical Force at 5 Hz mover reciprocating frequency**

Increase of frequency at the same current. Fig. 8 shows the thrust versus mover position characteristics at different currents. At centre position as the mover is at an equidistance from both the stators, at centre the force will be minimum and as it moves towards any one of the stator cores, attractive force increases and repulsion force decreases and the total force becomes maximum at the either end. Fig. 9 shows comparison of measured and theoretical forces at 5 Hz mover reciprocating frequency

### Conclusions

Finite element analysis based design and development of an direct drive axial flux PMLM suitable for low frequency and short stroke application is developed in the laboratory and various investigation tests are conducted and presented in this paper. Analytical solution to the forces and determination method of the integral parameters of a PMLM are shown. Finite element method with FEMLAB6.0 with Mathworks is used for the field analysis of the different values of the exciting current and for variable mover position. Computer simulations for the magnetic field distribution, forces are shown. The Prototype has been operated in the oscillatory mode with small loads at low frequency up to 5 Hz. The theoretically calculated results are compared with the measured ones and FEA Simulations, and found to be in good conformity. This can be

successfully applied for low frequency short stroke applications like heart pumps.

### References

- G. Kang, J. Hong, and G. Kim. 2001. Design and analysis of slotless-type permanent-magnet linear brushless motor by using equivalent magnetizing current. *IEEE Ind. Appl.* 37:1241–1247.
- N. Sadowski, R. Carlson, A. M. Beckert, and J. P. A. Bastos. 1996. Dynamic modeling of a newly designed linear actuator using 3D edge elements analysis. *IEEE Trans. Magn.* 32: 1633–1636.
- S. Vaez-Zadeh and A. Isfahani. 2006. Multi-objective design optimization of air-core linear permanent-magnet synchronous motors for improved thrust and low magnet consumption, *J. IEEE Magn.* 42:446–452.
- B. Tomczuk and M. Sobol. 2003. Influence of the supply voltage on the dynamics of the one-phase tubular motor with reversal motion. *Proc. 39th Int. Symp. Electrical Machines—SME'2003. Gdansk/Jurata, Poland.* 417–426
- D. G. Taylor and N. Chayopitak. 2006. Time-optimal position control of electric motors with steady-state temperature constraints. *Proc. IEEE Int. Symp. Industrial Electronics Montreal, QC, Canada.* 3142–3146.
- M. Athans and P. L. Falb. 1966. *Optimal Control*. New York: McGraw Hill,
- H. D. Chai. 1998. *Electromechanical Motion Devices*. Upper Saddle River, NJ: Prentice Hall,
- W. H. Hayt. 2006. *Engineering Electromagnetics*. New York: McGraw Hill,
- S. A. Nasar and I. Boldea. 1987. *Linear Electric Motors*. Englewood Cliffs, NJ: Prentice-Hall.
- Kou Baoquan, Li Liyi, and Zhang Chengming. 2009. Analysis and Optimization of Thrust Characteristics of Tubular Linear Electromagnetic Launcher for Space-Use. *IEEE Trans. Magn.* 45: 250-255.
- Ge Baoming, Anibal T. de Almeida, and Fernando J. T. E. Ferreira. 2009. Design of Transverse Flux Linear Switched Reluctance Motor. *IEEE Trans. Magn.* 45:113-119.
- Iakovos St. Manolas, Antonios G. Kladas, and Stefanos N. Manias. 2009. Finite-Element-Based Estimator for High-Performance Switched Reluctance Machine Drives. *IEEE Trans. Magn.* 45:1266-1269.



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**TABLE I**  
**PMLOM DESIGN PARAMETERS**

Rated Input Voltage	75V
Rated input power	175 watts
Stroke length	15 mm
Outer Diameter (Stator)	60 mm
Stator core type	CRGO Silicon Steel
Thickness of lamination	0.27 mm
Stator length	50 mm
No. of turns in Coil aa',cc'	500
No. of turns in Coil bb',dd'	250
Coil resistance	21 ohms
Slot depth	35 mm
Permanent Magnet Type	Rare Earth
Permanent Magnet Length	2 mm
Coercivity	750000 A/m
Remanence	1.5 T
Outer diameter (Mover)	50 mm
Shaft diameter	12 mm
Coil Inductance	0.21 Henry