



A Mathematical Formulation of Inductance for Multipole Field Electromagnetic Launcher

K.Sri Chandan, P. Mallikarjuna Rao,
Research Scholar, Professor

Department of Electrical Engineering Andhra University,
Visakhapatnam, India
electricalprofessor@gmail.com, srichandank@gmail.com

April 30, 2018

Abstract

Calculation of inductance is the key point for electrical propulsion, as the performance parameters depend on inductance value. In this paper, an inductance formula is derived based on the flux distribution to develop the parametric magnetic network model for Multipole Field Electromagnetic Launcher (MFEML). To account the magnetic field effect in the launcher, multiple flux paths are considered to estimate the inductance profile. The theoretical analysis and numerical simulations are performed and validated using Finite Element Analysis.

Key Words: Multipole field, Flux distribution, Magnetic Equivalent circuit, FEA.

1 Introduction

The intensifying demand for the linear motion of various automatic and robotic applications, electromagnetic launchers are becoming more and more desirable. Multipole Electromagnetic Launchers has the potential of developing huge thrust force, large driven mass,

super velocity launch and steady maglev compared to conventional electrical launchers [1]-[3]. In [4], it is indicated that the projectile is accelerated with spinning motion about its axis which could keep the projectile fly stability. The present research of Multipole Field Electromagnetic Launcher (MFEML) is mainly concentrating on theoretical analysis and experimental verification. For example, Zhu et al. [1]-[3] proposed the concepts of normal and twisty MFEML; Luo et al. [7] analyzed different connection patterns of MFEML and experimentally tested a single-stage launcher. The above research demonstrated the characteristics of MFEML with an assumption that the basic principles of eddy-current catapult and multipole field induction acceleration are identical. And the Lorentz force is been calculated by neglecting the leakage fluxes. However, previous studies excluded the leakage fluxes and instead created an identical equivalent circuit for both the coils for the calculation of Lorentz force.

In this paper, a flux concentrated Multipole Field Electromagnetic Launcher is introduced. As the inductance varies according to the permeance waveform, it is necessary to analyze the relative permeance before calculating the inductance. Hence a new methodology is proposed to calculate permeance and further the inductance of the accelerating coils based on the position of the projecting object. The parameters are validated with Finite Element Analysis (FEA).

2 MAGNETIC NETWORK MODEL OF MFEML

Fig.1, (a) shows the basic structure of a Single stage Multipole Field Electromagnetic Launcher and (b) shows the catapult coil and induction coil of the MFEML

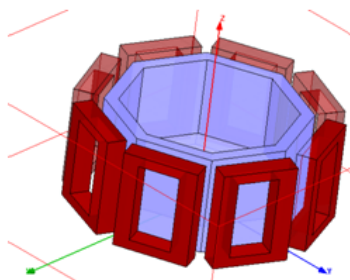


Fig. 1. (a) Basic Structure of Single stage MFEML

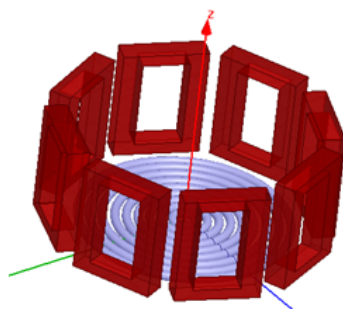


Fig. 1. (b) Catapult Coil and Induction Coil of MFEML

The working principle and the basic characteristics are elaborated in [1]-[3], in brief the catapult coil will give the initial push to the object and the induction coils will guide the object to move along the axis with high thrust. The catapult coil conductor is considered as cylindrical shape and it is kept in spiral arrangement. The induction coils and catapult coil are energized from a capacitor bank.

Fig. 2, (a) and (b) represents the flux flow diagram in a single coil of MFEML when object is inside and outside the coil respectively.

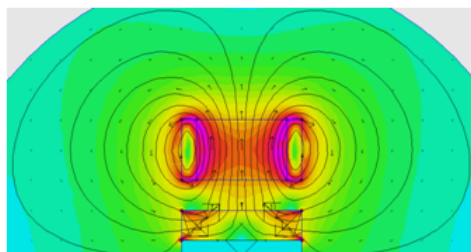


Fig. 2. (a) Flux lines in single coil of MFEML when object inside

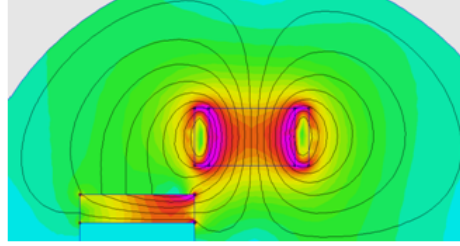


Fig. 2. (b) Flux lines in single coil of MFEML when object outside

The flux paths are equiflux lines (i.e., equal amount of flux lines are represented by each flux path). The flux distribution is symmetric with respect to the center line of the excited induction coil. The flux path 1 is assumed to have a flux of 1 in the induction coil. It crosses the air gap, splits evenly in the object, and then recrosses the air gap to the other side of the coil. The reluctances of the induction coil, air gap, and object for the flux path are denoted as R_c , R_g and R_p respectively. The magnetic circuit for a single coil is shown in Fig. 3.

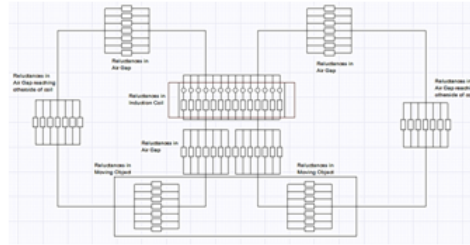


Fig. 3. The Magnetic Network Model of MFEML

In this model, different flux paths around the poles are considered to find the magnetic impedance of the magnetic equivalent model. Magnetic impedance is derived in terms of flux measured at the magnetic equivalent of the electrical terminals and the (MMF) reluctance between them. The magnetic parameters need more careful definitions as the magnetic flux flow in more regions with different areas. So the general objective in this section is to derive the permeances of each flux region, to find out the lumped equivalent inductance offered by the coils in the equivalent magnetic model.

This equivalent inductance is further used to evaluate/attain the force offered by the coils on the projecting body

The expressions for reluctance of the induction coil, air gap and object for the flux paths are derived and the expressions are presented in this section.

The Reluctance of Flux path 1

Reluctance in induction coil

$$R_{c1} = \frac{5l_c}{\mu_0\mu_r w_c(c-t)} \quad (1)$$

Reluctance in Air-gap

$$R_{g1} = \frac{40l_g}{\mu_0 w_p(4h_c + 5l_p - 9t)} \quad (2)$$

Reluctance in Moving Object

$$R_{p1} = \frac{\pi}{4\mu_0\mu_{rp}h_m w_p} \left(\frac{\sqrt{l_p^2 + h_m^2}}{2l_p} - 3 \frac{\sqrt{\left(\frac{3l_p+t}{4}\right)^2 + \left(\frac{2h_m}{3}\right)^2}}{(3l_p+t)} \right) \times \sqrt{\left(\frac{7l_p+t}{8}\right)^2 + \left(\frac{5h_m}{6}\right)^2} \quad (3)$$

Reluctance in air gap to reach other side of the coil

$$R_{og1} = \frac{4\pi(7h_m + 6l_g + 12l_c)}{3\mu_0 w_p h_m} \quad (4)$$

The Reluctance of Flux path 2

Reluctance in induction coil

$$R_{c2} = \frac{5l_c}{\mu_0\mu_r w_c(c-t)} \quad (5)$$

Reluctance in Air-gap

$$R_{g2} = \frac{40l_g}{\mu_0 w_p(4h_c + 5l_p - 9t)} \quad (6)$$

Reluctance in Projecting Object

$$R_{p2} = \frac{3\pi}{4\mu_0\mu_{rp}h_m w_p} \left(\frac{\sqrt{\left(\frac{3l_p+t}{4}\right)^2 + \left(\frac{2h_m}{3}\right)^2}}{(3l_p+t)} - \frac{\sqrt{\left(\frac{l_p+t}{2}\right)^2 + \left(\frac{h_m}{3}\right)^2}}{(l_p+t)} \right) \times$$

$$\sqrt{\left(\frac{5l_p + 3t}{8}\right)^2 + \left(\frac{h_m}{8}\right)^2} \quad (7)$$

Reluctance in air gap to reach other side of the coil

$$R_{og2} = \frac{2\pi(h_m + 3l_g + 6l_c)}{\mu_0 w_p h_m} \quad (8)$$

Where ,

l_c is length of the coil in meters

l_g is length of the air gap in meters

h_c is height of the coil in meters

l_p is length of the projecting object in meters

h_p is height of the projecting object in meters

h_m is height of the metallic sheath in projecting object in meters

w_c is width of the coil in meters

w_p is width of the coil in meters

t is thickness of the coil winding in meters

μ_0 is permeability of the air

μ_{rp} is relative permeability of the projecting object

n is number of turns

In a similar way, the reluctances of all the flux paths are been derived and the equivalent magnetic circuit is developed as shown in Fig. 4

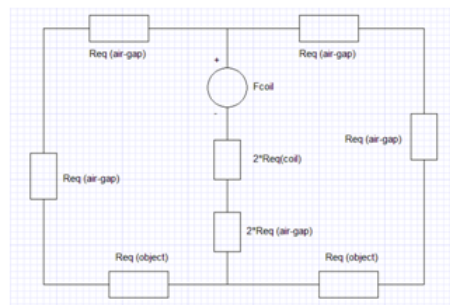


Fig. 4. The Magnetic Equivalent Circuit of MFEML

The complete inductance offered by the induction coil based on the position of the object is found using

$$L = \frac{N^2}{R_{total}} \quad (9)$$

The force generated on the projectile is derived from the electro-mechanical energy conversion principles as,

$$F = \frac{1}{2} i^2 \frac{dL}{dx} \quad (10)$$

The same methodology is followed for different position of the object i.e., when the object totally outside, just entering and while leaving the induction coil to estimate the inductance and force profile.

3 Inductance Calculation of catapult coil

The induction coils cannot provide the initial thrust because the force generated by the induction coil is three dimensional [3]. Due to which the object cannot move smoothly in the axis of the barrel. To overcome this problem, catapult coil is used in the MPEML, which provide the initial thrust such that the object is given the direction in which way it has to propel. In this section, the inductance offered by the catapult coil is presented. The catapult coil considered in this work is a cylindrical cooper wire in a spiral arrangement which is excited by a capacitor bank.

The inductance of the catapult coil is expressed as

$$L_c = \frac{N^2 A^2}{30A - 11D_i} \quad (11)$$

$$A = D_i + N_c \frac{(w + s)}{2} \quad (12)$$

Where

A= Area of the Spiral Coil

D_i = Inner Diameter of catapult coil

s= Distance between the coil winding

w=Wire diameter of catapult coil

N_c = Number of turns catapult coil

D_o =Outer Diameter catapult coil

The overall electrical equivalent circuit of MFEML is presented in Fig. 5.

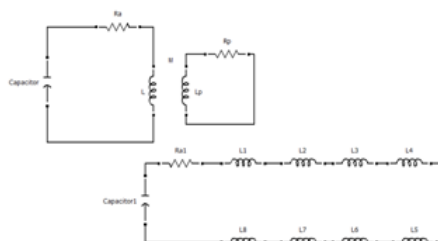


Fig. 5. Overall Electrical Equivalent circuit of MFEML

4 VALIDATION OF PROPOSED MEHTOD BY COMPARING INDUC-TANCES

The inductance profile of a single induction coil in MFEML is shown in Fig.6. It is observed that the maximum and minimum inductance of the induction coil when the projecting object is completely inside is 30.2 mH and 23 mH respectively.

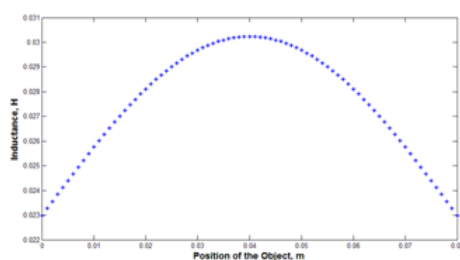


Fig. 6. Inductance Profile of a Single Coil of MFEML

To validate the inductance profile, Finite Element Analysis is implemented and flux distributions in the MFEML are plotted. The flux density and flux intensity plots are shown in Fig. 7, 8 & 9.

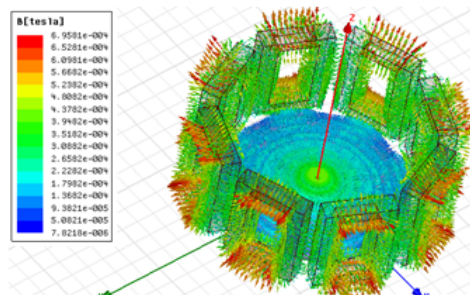


Fig. 7. Flux density profile of MFEML

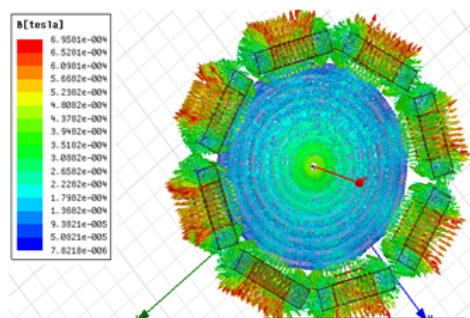


Fig. 8. Top view of Flux density profile in MFEML

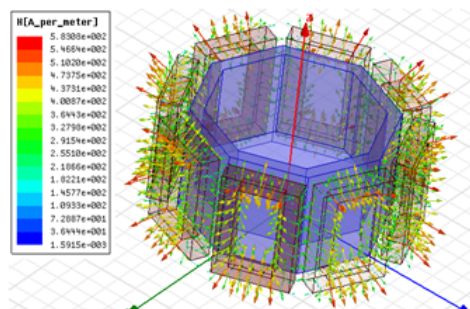


Fig. 9. Flux intensity profile in MFEML

From the finite element analysis, the maximum inductance value attained is 33 mH and the minimum inductance value observed is 24 mH. And the comparison plot between the proposed method and FEA are shown in Fig. 10.

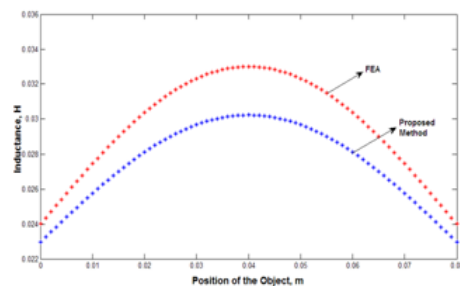


Fig. 10. Comparison of Inductance Profile

TABLE 1. SYSTEM PARAMETERS

Induction Acceleration Coil	
Length of the Coil	0.02m
Length of the Air gap	0.01m
Height of the Coil	0.04m
Length of the Projecting object	0.04m
Height of the Projecting object	0.02m
Height of the Metallic sheath in projecting object	0.01m
Thickness of the Coil winding	0.01m
Number of Coils	8
Permeability of the Air	$4\pi \times 10^{-7}$
Number of Turns	500
Material	Copper
Catapult Coil	
Material	Copper
Inner diameter	0.01m
Outer diameter	0.04m
Number of Turns	30
Projecting Object	
Material	Steel 1008

5 Conclusion

This article introduces a flux concentrated Multipole Field Electromagnetic Launcher. New formulae for inductance of an acceleration coil of MFEML based on the flux distribution method are derived. Mathematical based magnetic circuit model is developed considering the flux leakages. The method proposed here can easily be applicable for inductance calculation of coils of any random size and shape. The proposed method values are validated with finite element analysis.

References

- [1] Y. Zhu, Y. Wang, Z. Yan, L. Dong, X. Xie, and H. Li, Multipolefield electromagnetic launcher, IEEE Trans. Magn., vol. 46, no. 1, pp 2622- 2627, Jun. 2010
- [2] Antonino Musolino, Rocco Rizzo, and Ernesto Tripodi, Travelling Wave Multipole Field Electromagnetic Launcher: An SOVP Analytical Model, IEEE Transactions On Plasma Science, Vol. 41, No. 5, May 2013
- [3] Xinpeng Xue, Tao Shu, Zhiyong Yang, and Gang Feng, Toroidal Field Electromagnetic Launcher, IEEE Transactions on Plasma Science, Vol. 44, No. 10, October 2016.
- [4] Zhu Yingwei, Wang Yu, Chen Weirong, Yan Zhongming, and Li Haitao, Analysis and Evaluation of Three-Stage Twisty Octapole Field Electromagnetic Launcher, IEEE Transactions On Plasma Science, Vol. 40, No. 5, May 2012
- [5] Frederick W. Grover, Inductance Calculation, Dover Publication, 2009.
- [6] Xinpeng Xue, Tao Shu, Zhiyong Yang, and Gang Feng, A New Electromagnetic Launcher by Sextupole Rails: Electromagnetic Propulsion and Shielding Numerical Validation, IEEE Transactions On Plasma Science, Vol. 45, No. 9, September 2017.
- [7] Wenbo Luo, Yu Wang, Zhixing Gui, Zhongming Yan, and Weirong Chen, Connection Pattern Research and Experimental Realization of Single Stage Multipole Field Electromagnetic Launcher, IEEE Transactions On Plasma Science, Vol. 41, No. 11, November 2013
- [8] Ahmadali Khatibzadeh, M.R. Besmi, Improve Dimension of Projectile For Increasing Efficiency of Electromagnetic Launcher, 4th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2013), Feb 13-14,2013, Tehran, Iran. 78-1-4673-4484-5/13 2013 IEEE.

- [9] Zhongming Yan, Xiaofei Long, Falong Lu, Yu Wang, and Hanjun Liu, Study of Single-Stage Double-Armature Multipole Field Electromagnetic Launcher, IEEE transactions on plasma science, vol. 45, no. 8, August 2017
- [10] Rafael Mendes Duarte and Gordana Klaric Felic, Analysis of the Coupling Coefficient in Inductive Energy Transfer Systems, The University of Melbourne, Parkville, VIC 3010, Australia, Volume 2014 (2014), Article ID 951624, 6 page, 2014.
- [11] Smythe, w., (1939), "Static and Dynamic Electricity," McGraw-Hill Book Co., Inc., New York, First edition (1939), 316.
- [12] C. D. Sijoy and Shashank Chaturvedi , Calculation of Accurate Resistance and Inductance for Complex Magnetic Coils Using the Finite-Difference Time-Domain Technique for Electromagnetic, IEEE Transactions On Plasma Science, Vol. 36, No. 1, February 2008.
- [13] Y. P. Su, Xun Liu and S. Y. Ron Hui, Mutual inductance Calculation of Movable Planar Coils on Parallel Surfaces, IEEE Transactions On Power Electronics, Vol. 24, No. 4, April 2009.
- [14] John T. Conway, Inductance Calculation for Non coaxial Coils Using Bessel Functions, IEEE Transactions on Magnetics, Vol. 43, No. 3, March 2007.
- [15] Slobodan Babic and Cevdet Akyel, Improvement in calculation of the self and Mutual Inductance of Thin wall Solenoids and Disk Coils, IEEE Transactions on Magnetics, Vol. 36, No. 4, July 2000.
- [16] Babic, S. I. and C. Akyel, New analytic-numerical solutions for the mutual inductance of two coaxial circular coils with rectangular cross section in air, IEEE Trans. Mag., Vol. 42, No. 6, 1661-1669, Jun. 2006
- [17] K. Sri Chandan, P. Mallikarjuna Rao, Comprehensive Analysis of Octapole Electromagnetic Launcher, International Journal for Research in Applied Science & Engineering Technology (IJRASET), Volume 5 Issue 10, October 2017.

- [18] Sandhya Thotakura, Mallikarjuna Rao Pasumarthi, A New Method for Computation of Dynamic Inductance of Tubular Motor, Journal of Electrical Engineering, November 2017.

BIOGRAPHY

K. Sri Chandan is currently a research scholar in Andhra University, Andhra Pradesh, Visakhapatnam, India. (e-mail:srichandank@gmail.com).

Dr. P. Mallikarjuna Rao is currently with Andhra University, Visakhapatnam, Andhra Pradesh, India, where he is a professor of Electrical Engineering. His research interests include control systems, Design and analysis of specific purpose electrical machines and their control. (email:electricalprofessor@gmail.com).