1-1-2012

Reducing cogging force in a cage-secondary linear induction motor (LIM) by one-side shifting

Mochammad Rusli
University of Wollongong, mr402@uowmail.edu.au

Recommended Citation

Rusli, Mochammad, "Reducing cogging force in a cage-secondary linear induction motor (LIM) by one-side shifting" (2012). *Faculty of Engineering and Information Sciences - Papers: Part A*. 4254.
https://ro.uow.edu.au/eispapers/4254

Reducing cogging force in a cage-secondary linear induction motor (LIM) by one-side shifting

Abstract

High precision linear machining tools is one of interesting research field in related to high qualitative products which is also becoming one of competitive factor. The movement precision can be affected by existence of ripple force, unpredicted external load and frictional force. The existence of cogging force is the one limited factor of the linear precision. The reduction of cogging force of its linear movement precision of machining tools using rotary motor drive can be obtained by the skewed rotor or implement the feedback control system. Many researchers have conducted the reduction of cogging torque of its machining tools drive supported by using a feedback control algorithm variation concepts. Because of the great opportunity of construction variation in linear motors, this paper proposes to investigate an innovation of the cage secondary Double sided linear induction motor construction aimed to obtain the zero cogging Force. The cogging force can be predicted by investigated of the variation of stored energy magnetic in the air gap. Therefore, at first in this paper the implementation of estimation flux path in multi-tooth model in which is built as similar construction to the cage single sided linear induction motor, and will be verified by building experimental multi-tooth test-bed. Based on that multi-tooth experiment and the justification of estimation flux path method, the double-sided linear induction motor with offset position between both sided will be developed with the assumption that the cogging force will be able to cancel each other. In this paper will be described the arrangement of LIM model using FEM software and simulated. This motors consist of two layers, moving and stationary part. The stationary part are arranged as the cage-ladder structure.

Keywords

induction, linear, secondary, cage, force, cogging, shifting, reducing, side, one, lim, motor

Disciplines

Engineering | Science and Technology Studies

Publication Details

Rusli, M. (2012). Reducing cogging force in a cage-secondary linear induction motor (LIM) by one-side shifting. The 6th Electrical Power, Electronics, Communications, and Informatics International Seminar (pp. A2-1-A2-7). Malang, Indonesia: Brawijaya University, Indonesia.

Reducing Cogging Force in A Cage-secondary Linear Induction Motor (LIM) by One-Side Shifting

Mochammad Rusli 1) 2)
1)School of Mechanical, Materials and Mechatronic Engineering,
Faculty of Engineering, University of Wollongong, NSW, Australia
2)Electrical Department Faculty of Engineering, University of Brawijaya, Indonesia
mochammad.rusli@gmail.com

Abstract— **High precision linear machining tools is one of interesting research field in related to high qualitative products which is also becoming one of competitive factor. The movement precision can be affected by existence of ripple force, unpredicted external load and frictional force. The existence of cogging force is the one limited factor of the linear precision. The reduction of cogging force of its linear movement precision of machining tools using rotary motor drive can be obtained by the skewed rotor or implement the feedback control system. Many researchers have conducted the reduction of cogging torque of its machining tools drive supported by using a feedback control algorithm variation concepts. Because of the great opportunity of construction variation in linear motors, this paper proposes to investigate an innovation of the cage secondary Double sided linear induction motor construction aimed to obtain the zero cogging Force. The cogging force can be predicted by investigated of the variation of stored energy magnetic in the air gap. Therefore, at first in this paper the implementation of estimation flux path in multi-tooth model in which is built as similar construction to the cage single sided linear induction motor, and will be verified by building experimental multi-tooth test-bed. Based on that multi-tooth experiment and the justification of estimation flux path method, the double-sided linear induction motor with offset position between both sided will be developed with the assumption that the cogging force will be able to cancel each other. In this paper will be described the arrangement of LIM model using FEM software and simulated. This motors consist of two layers, moving and stationary part. The stationary part are arranged as the cage-ladder structure.**

Keywords— **Cogging Forces, Electromagnetic Field, Double sided-Linear Induction Motors**

I. INTRODUCTION

The demands for high precision machining are rapidly increasing, especially in industrial processes such as semiconductor manufacturing or metal cutting machine tools[1]. For machine tools in particular, the current international competitive levels of precision are below $1mm$ Linear Motors can offer significant advantages over rotary motors for driving linear machine tool axes, in that they either reduce or completely eliminate many of the performance limiting factors associated with rotary-linear translation methods[2]. The most common linear motor used in precision machine tools is the permanent magnet linear motor, particularly in high speed applications[3]. However, permanent magnet linear motors have a major disadvantage in precision metal cutting as the metallic dust and swarf associated with these processes can be attracted by the permanent magnets, which are typically along the entire length of the axis. Therefore, alternative linear motor technologies, such as the Linear Induction Motor (LIM), offer great potential as a solution for precision linear metal cutting axes.

One design aspect of linear motors that is important from a precision machining perspective is the minimization of cogging. Cogging is represented in linear machines as a variation in the magnetic forces along the machine axis, and can have a severe impact on the overall precision of the axis. For rotary motors, many researchers have reduced the cogging effect by using the feedback controller design or skewed rotor of motors. In linear induction motor, cogging effect can be reduced by modification of its construction, because linear motors have the great opportunities to modify the construction forms. This paper will present the investigation of the modification of A Cage-secondary Double Sided Linear induction motor with cogging effect nearly zero value.

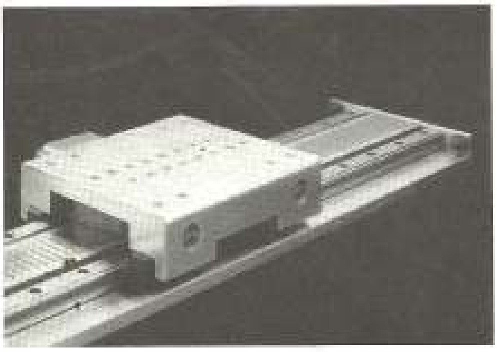

Figure 1: cage-secondary single-sided LIM (Photo Courtesy of Krauss Maffei Automationstechnik GmbH.

Minimization of the cogging effect in LIMs requires knowledge of the variation of stored magnetic energy in the air-gap. The calculation of magnetic circuits, where the air-gap permeance the magnetic flux and the flux density distribution are determined, is one of the most difficult problems in electrical machines[3]. Due to slotted cores, many researchers approximate the air-gap permeance in relation to magnetic energy stored in the air-gap. This paper proposes also to describe developing of the estimation of flux path in linear Induction motor construction in understanding the variation of cogging force in the air gap. The cogging force analysis based on the prediction of variation of stored magnetic energy in the air gap of motor. The calculation of the cogging forces will be conducted by using FEM approximation and EFP method. The both method will be compared and provide the relationship between difference relative position of the side in the DSLIM and the opportunity for reducing cogging force.

II. PROPOSED MODEL

Figure 2 shows the common a cage-secondary DSLIM which it will be described in this paper. It consist of two main parts, moving part and stationary part. The three phases AC electrical signal are impressed into coils placed in the slots of stationary part. The winding system based on the common structure in rotary AC machines. The stationary part is divided into two layer, the left side layer and right layer. Each layer have been designed with same number of slots, 9 slots in three poles pitch of winding.

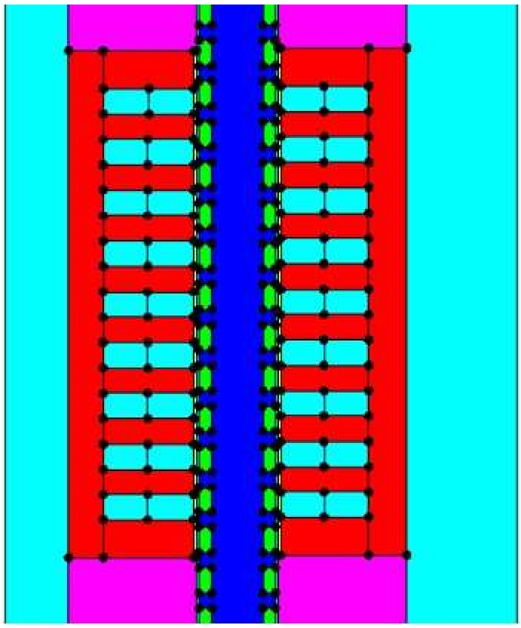

Figure 2: proposed model of LIM

This paper proposes to describe the cogging reduction can be obtained by one-side shifting of this motor. The proposed model will be built in the FEM-software for investigation the distribution of flux density quantity if the one of side are shifted. The flux density and cogging force prediction will be calculated by using the Estimation Flux Path (EFP) method. Based on that prediction equation, the one-side shifting length will be determined numerically.

III. COGGING FORCES

According to Arger [4] the term “cogging” can be defined as the “variation in the motor torque as it turns slowly”. Based on this definition, “cogging in an LIM can also be described as the variation of electromagnetic forces. The existence of cogging forces can be detected by energy variation or the magnetic energy gradient[4]. The direction of cogging forces is perpendicular to the air gap or called as tangential forces.

Each devices that consist of the some magnetic circuits especially that is implemented in electrical machines, including linear induction motors, the interaction between magnetic material, produced by nature – permanent magnet – or by electrical current source – electromagnet, with the iron core will effect generating of the attractive forces. When the rotor of motors exhibit a movement from one position to the other position, it can be change the direction of the attractive force in both surfaces of materials.

The position of iron core to the magnetic materials determines the direction of the attractive force. The cogging force can be manifested as the projection of the attractive force in the x-axis of movement. The cogging force in linear induction motors can be also referred to cogging force in permanent magnet motors.

In permanent magnet motor, cogging torque arises from the interaction of the rotor magnets with the steel teeth on the stator[5]. Yoshimura et al.[6] predict the existence of cogging force associated with the interaction between magnet end and the steel teeth of the primary winding.

The cogging force is a function of position and independent of the load angle. Due to the slotted nature of the primary core, the cogging force is periodic and repeat itself over every slot pitch[7]. Cogging torque is produced by the interaction between permanent magnet (PM’s) and slotted iron structure and manifests itself by the tendency of a rotor align in a number of stable positions even when motor not energized[8]. However in Linear Induction Motors (LIMs), energy magnetic variation in the air gap can be used for prediction of the cogg8ng foces [9].

Because of the electromagnetic interaction between the exterior teeth of the armature core and the permanent magnets, the cogging force is inevitable in both a short primary type and short secondary type PMLM [10]. As in rotary PM machines, linear PM motors can exhibit significant cogging forces due to interaction of the permanent magnet in the stator and with the iron in the stator[11].

Based on the above explanation, it can be concluded that cogging forces are: (a) that effected by the interaction between edge of certainty magnet and the slotting iron core; (b) a function of the position and independent to load angle; (c) is periodic and repeat itself over every slot pitch.

Analogy to the cogging force in permanent magnet motors, it can be defined that the cogging forces in a linear induction motor might be caused by the interaction between edge of electromagnet on primary section with the slotted iron core in secondary layer. It should be independent to the load angle and periodic according to slot pitch.

IV. GEOMETRIC PARAMETERS STANDARD DESIGN

This LIM-model design will be initialized by calculating of geometric parameters of DSLIM. design parameters of upper side of Double-sided Linear Induction motor using standard procedures. Because the DSLIM consist of principally two sides that have symmetry dimensions each other. Therefore design concept would be developed only in one side. The upper sided design procedure are referred by standard design of main dimension calculations and electrical dimension. The number of slot and winding system will be given as the first step of design.

The first important parameter in designing linear induction motor is pole pitch. The pole pitch is defined as the distance between slots where some three phase windings for one pole are connected. Due to significant influence of pole pitch to the synchronous velocity of such as linear induction motor, thus pole pitch could be calculated by using equation that describe relationship between synchronous velocity and pole pitch.

$$\boldsymbol{v_s} = (2.\boldsymbol{f})\boldsymbol{\tau} \tag{1}$$

Where:

v_s : synchronous velocity

f : three phases signal input frequency

τ : Pole pitch

If the synchronous velocity is given 6 m/s, so pole pitch for that Linear Induction motor should be:

$$\tau = \frac{6}{100} = 0.06\boldsymbol{m} = 60\boldsymbol{mm} \tag{2}$$

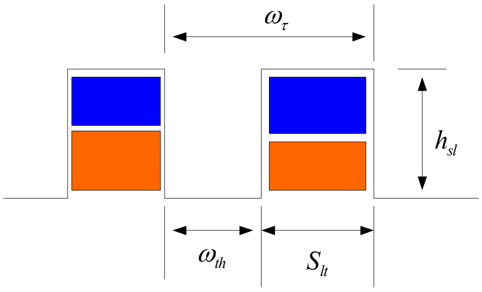

Figure 3: sketch of two slots in the moving part

The next main dimension of moving part of linear induction motor is slot pitch. This parameter reveals the distance between slots in moving part of LIM. The slot pitch could be related to the dimension of slot- and tooth- width of motor. Parameters which refereed to slot pitch are tooth width ($\omega_{t\,th}$), slot width (S_{slt}), totally number of slot (Z_1') and number full filled slot (Z_1). The winding system in this design are given as double winding with 3 slots are half filled. Slot pitch can be calculated using the equation (see fig. 3)

$$\boldsymbol{\omega_\tau} = \boldsymbol{\omega_{th}} + \boldsymbol{S_{slt}} = \frac{2.\boldsymbol{p}.\boldsymbol{\tau}}{\boldsymbol{Z}_1'} \tag{3}$$

The pole number is given that of as 2, so slot pitch can be obtained by:

$$\boldsymbol{\omega_\tau} = \frac{2*0.06}{9} = \frac{0.1}{9} = 13.33\boldsymbol{mm} \approx 15\boldsymbol{mm} \tag{4}$$

For improving the distribution of magnetic flux density and reduce the resistance and reactance, this linear induction motor use chorded winding system. Based on the construction of chorded winding system, there is parameter called coil pitch parameter. It can be determined based on the slot pitch. Because was given the number of slot in which consist only half filled coil, so the coil pitch should be:

$$\boldsymbol{\omega_c} = 2*13.33 = 26.66\boldsymbol{mm} \approx 30\boldsymbol{mm} \tag{5}$$

Totally, the length of primary layer can be obtained with addition of multiplication of number pole with pole pitch and coil pitch and end distance. The end width of primary in this design will be defined as that of 10 mm. Thus the length of primary layer is:

$$\boldsymbol{L_\tau} = 2\boldsymbol{p}*\boldsymbol{\tau} + \boldsymbol{\omega_c} + \boldsymbol{c}_1 = 2*60+30+15=165\boldsymbol{mm} \tag{6}$$

The rated thrust of small and large linear induction motor depend on the area of primary layer. According the previous designer, that for small linear induction motor for rated thrust which have thrust bigger than 100 N, the ratio between rated thrust and the area of primary layer approximately is:

$$\frac{F_x}{A} = 5000 \ \ (N/m^2)$$

(7)

Then we can calculate area of primary layer:

$$\boldsymbol{A} = \frac{\boldsymbol{F_x}}{6000} = \frac{100}{6000} = 0.017\boldsymbol{m}^2 = 17000\boldsymbol{mm}^2 \tag{8}$$

The area of primary layer is multiplication between depth and width of primary layer. Because primary width has already calculated, so The primary depth may be obtained easily.

$$\boldsymbol{L_i} = \frac{\boldsymbol{A}}{\boldsymbol{L_\tau}} = \frac{17000}{165} = 103.03 \approx 100\boldsymbol{mm}$$

(9)

The three phases AC current signal flowing in primary coil generated the travelling magnetic flux in air-gap. This magnetic flux influence or induced voltage signal into the secondary layer of LIM. Typically, the induced voltage in secondary layer is approximated about a half of the rms value of input voltage signal.

$$E_i \approx 0.5 * V_i = 110Volt \text{ (rms values)} \tag{10}$$

And input current in coil of primary layer:

$$\boldsymbol{I_i} = \frac{\boldsymbol{F_x} * \boldsymbol{v_i}}{\boldsymbol{m_{ph}} V_1 \boldsymbol{\eta} \cos\boldsymbol{\phi}} \geq \frac{100*3.5}{3*220*0.115} \geq 8\boldsymbol{Ampere} \tag{11}$$

The number of turn per phase is calculated by using variation of electromagnetic power (EP). The AC current signal flowing in primary coil generate the travelling magnetic flux. The output coefficient for primary can also determined with modification of carter coefficient.

$$P_{elm} = m_{ph} * E_1 * I_i \approx 7.59VA \tag{12}$$

$$\sigma_p = \frac{P_{elm}}{V_{sc} * A} \approx \frac{7.591520}{5*4.6} \approx 15000VA/m^2 \tag{13}$$

Based on the output coefficient line current density and the output coefficient, with assuming that $B_z = 0.4T$, approximately line current density can be calculated by using f this methods)

$$J_y = \frac{m_{ph}\sqrt{2} * I_i N_1}{B_z} = -\frac{32000}{0.4} \approx 88900A/m \tag{14}$$

Therefore number of turn per phase is:

$$N_1 = \frac{88900*0.05*2}{3\sqrt{2}*2.3} = 449 \approx 450Turn \tag{15}$$

The width of air-gap is assumed = 0.5mm And the width of teeth will be taken as 5.5mm

$$\omega_{th} = 5.5 \tag{16}$$

$$S_{lt} = \omega_\tau - \omega_\tau = 5.5mm \tag{17}$$

For single sided linear induction motor, the thickness of back Iron can be calculated using the following equation. However for double-sided linear induction motor, the thickness of secondary layer can be obtained by the subtraction the back iron thickness with air-gap and primary high.

$$\boldsymbol{d}_1 = \boldsymbol{L_i} + 0.1*\boldsymbol{\tau} = 0.075 + 0.1*0.06 = 0.030\boldsymbol{m} = 30\boldsymbol{mm} \tag{18}$$

The slot high may be determined by using ratio typical flux density normal and tangential and pole pitch. Detail equation are:

$$h_{sl} = 0.3 * \tau * \frac{B_n}{B_t} = 0.3 * 0.050 * \frac{1.6}{0.7} \approx 0.0342 \approx 35mm \tag{19}$$

The thickness of aluminum can be defined as $\boldsymbol{d}_2 = 5\boldsymbol{mm}$.

TABLE 1:
DESIGN RESULTS

No.	Parameter	Symbol	Value	Unit
1	Pole pitch	τ	60	Mm
2	Current Per phases	I_i	8	A
3	Primary depth	L_i	100	Mm
5	Aluminum thickness	d_2	5	Mm
6	Back iron thick-ness	d_1	30	Mm
7	Slot width	S_{slt}	10	Mm
8	Teeth width	W_{th}	10	Mm
9	End section	ω_{end}	10	Mm
10	Turn number	N_1	951	
11	Number of slot of full	Z_1	9	
12	Height of slot	h_y	35	Mm

V. OFF-SET POSITION OF MOVING PART LIM-MODEL

The double sided linear induction motor consist of two parts, secondary and primary layer. The secondary part are placed in between the double primary layers in which the electrical current flowing into the coils placed to their slots. The secondary layer compose of some cages or ladders circuits that made of aluminum. Figure 1 shows the simulated DSLIM model in the flux software version 10.2.1 produced by Cedrat [12].

In each primary part compose of 9 slots in which AC three phase signal current are flowed into them. The arrangement of the three phase winding in similarity to the rotary induction motors. The moving part is the secondary layer and fixed part is the primary layer. The The cage width (secondary tooth) of secondary are specified as 6 mm (less than the tooth width of primary – 10mm), for fulfilling the starting requirement. The secondary and primary slot are defined with the same values, each is 10 mm.

The measurement of cogging action in this model are conducted by using the multi-static option. The cage-secondary are made in open circuit condition, so that there is no electrical current flowing in them. After the coils are supplied by electrical current, the primary layer are moved in 1 mm step in positive direction (up direction). Because of there is no current flowing in the ladder, in the secondary occur the electromagnetic forces (attractive and repel forces). The electromagnetic force that have the tangential direction in this model the magnetic forces varies up and down called cogging action.

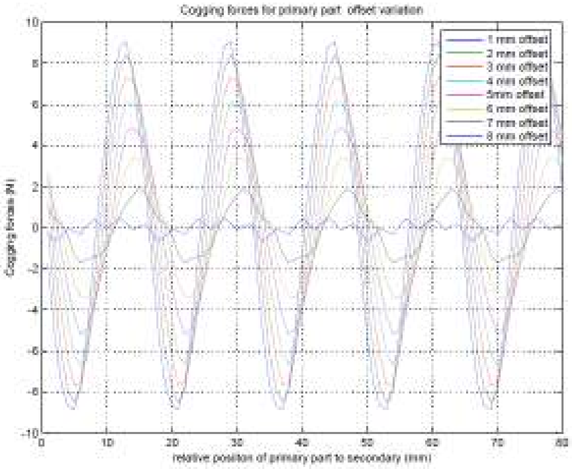

Figure 4: the cogging forces by the offset position variation

The investigation for variation of offset position between left and right side of model have been conducted. By using the finite element method, the simulation results show that the offset-position of both sides could provide the minimum cogging forces. Figure 4 shows that the minimization of cogging can be obtained in the 8 mm offset model.

Figure 5 shows the tangential flux densities in the left and the right side of the air gap of LIM model. The tangential flux density in both sides could be cancelled each other. The normal flux densities also looks symmetry, so the reduction of electromagnetic forces in the tooth will be minimized.

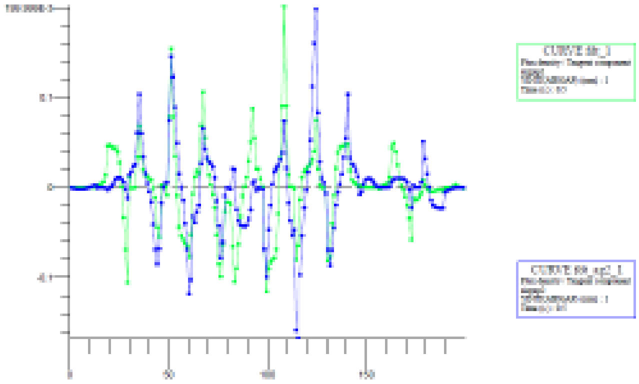

Figure 5: Tangential Flux density in the left and right air-gap

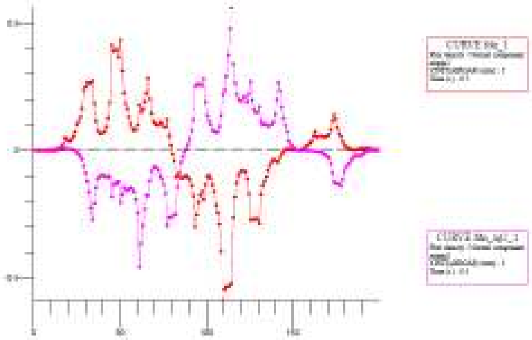

Figure 6: Norma Flux density in the left and right air-gap

TABLE 2:
COMPARISON BETWEEN REC. MODEL AND OFFSET 12 MM

t-width (mm)	thrust No offset	Thrust 12_ofset
4	72.84	65.10
5	77.32	69.11
6	83.53	74.66
7	88.94	79.49
8	93.43	83.51
9	96.5	86.25
10	101.63	90.84
11	104.67	93.55
12	107.25	101.92
13	113.64	101.57
14	119.58	106.88
15	124.87	111.61

The designed LIM-model have simulated by using Cedrat Flux Software. By the slot pitch variation from 4 until 15 mm, The investigation of the useful thrust between no offset model and 12mm offset-model shown that provide the slight difference between them. Table 2 show the comparison results of shifted one side of LIM-model in 12 mm length

Figure 7 shows the distribution magnetic field in all of regions of the 8 mm ffset model. The circle of magnetic field between both sides are similar, therefore the useful thrust in the both air gap have a similar direction. the 8mm-offset model. In this paper will be shown the cogging forces investigation results of that model, if the right side of model would be shifted up in step 1 mm. Table 3 shows simulation results of useful thrust of offset model.

The offset position length variation in the simulations results influences the useful thrust significantly compared with the no offset-model.

TABLE 3:
COMPARISON THRUST FOR OFFSET VARIATION

speed m/s	ofset 5 Thrust(N)	ofset 6 Thrust(N)	ofset 7 Thrust(N)	ofset 8 Thrust(N)
6	0	0	0	0
5.75	15.34	15.44	19.08	19.42
5.5	34.65	34.8	34.24	34.58
5.25	43.66	43.78	43.86	44.2
5	53.7	53.75	53.82	54.16
4.75	63.02	63.17	63.23	63.57
4.5	71.63	71.75	71.78	72.12
4.25	77.45	77.67	77.76	78.1
4	83.52	83.7	83.85	84.19
3.75	87.35	87.32	87.43	87.77
3.5	89.55	89.77	89.82	90.16
3.25	90.67	90.86	90.92	91.26
3	91.01	91.09	91.17	91.51
2.75	90.21	90.4	90.4	90.74
2.5	88.56	88.99	89.04	89.38
2.25	86.43	86.54	86.65	86.99
2	84.66	84.71	84.88	85.22
1.75	83.07	83.18	83.23	83.57
1.5	78.23	78.39	78.87	79.21
1.25	76.33	76.45	76.56	76.9
1	72.01	72.06	72.23	72.57
0.75	69.23	69.37	69.54	69.88
0.5	65.44	65.67	65.88	66.22
0.25	69.45	69.57	69.65	69.99
0	57.13	57.24	58.33	58.67

Table 3 sows that the offset variation from 5 until 8 mm could only provide the useful thrust much smaller compared the no-offset model. The offset in 12 mm, the model could be made bigger thrust (see table 2). However the cogging force by the 12mm offset length is still higher than the other model. Therefore the cogging force will be investigated only in the 9 mm and 12 mm offset. Table 4 shows that cogging forces on both offset model can be reduced into under 10% compared the useful thrust.

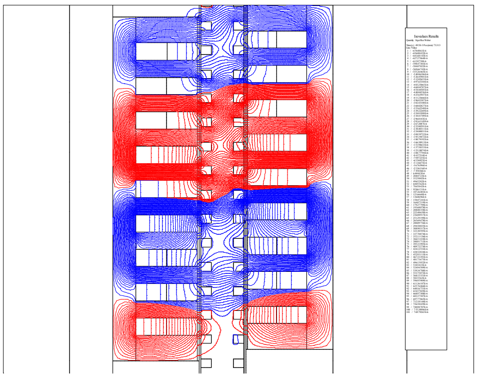

Figure 7 : proposed 8mm-off-set model

TABLE 4:
PERCENT OF COGGING OVER THRUST FOR 12MM AND 9 MM OFFSET MODEL

offset (mm)	cogging 12 mm	cogging 9 mm	thrust 12mm	thrust 9 mm	percent 12 mm	percent 9 mm
4	8.29	8.16	89.65	84.53	9.24707	9.65338
5	9.09	7.92	91.01	85.03	9.98791	9.31436
6	9.5	9.28	91.09	85.12	10.4292	10.9023
7	9.55	6.52	91.17	85.23	10.4749	7.64989
8	9.75	8.6	91.41	85.54	10.6662	10.0538

VI. CONCLUSION

The cage secondary LIM model with double layer moving part might generate the high useful thrust and also would used for reducing the cogging force. The reducing cogging would be developed by compensation way in which the one side will be up-shifted in order to the flux magnetic in both sides would be cancelled each other. By using finite element, the reducing cogging forces on this model could be forced down until under 10% compared the useful thrust values Although the offset-model can reduced cogging forces, however the useful thrust value are in 12% lower than no-offset LIM-model.

REFERENCES

[1] Kok Kiong Tan, Hui Fang Doi, Yang quan Chen and Tong Heng Lee, High Precision Linear Motor Control Via Relay-Tuning and Iterative Learning Based on Zero-Phase Filtering, IEEE Transactions on Control Systems Technology, Vol. 9, No. 2,pp244-253, March, 2001.

[2] S. B. Yoon, J. Hur, and D.S. Hyun, **A Method of Design of Single-Sided Linear Induction Motor for Transit**, IEEE Transactions on Magnetics, Vol. 33, No. 5, September 1997

[3] Gieras, J. F., Linear Induction Drives, Clarendon Press, Oxford, 1994.

[4] Philip L. Arger, Induction Machines, Gordon and Breach Science Publishers, New York, 1961.

[5] Moscorop, J., Commins, P., Cook, C., Torque Perturbations and Dynamic Stiffness of Linear Motors for Grinding Machines, University of Wollongong, Australia, 2003.

[6] Lee, B.J., Koo, D H, Cho Y H, Investigation of Secondary Conductor type of linear Induction Motor Using the Finite Element Method, Proceeding of IEEE the 2008 International Conference on Electrical Machines, 2008.

[7] G. Brandenburg, S. Brueckl, J. Dormann, J. Heinzl, C. Schmidt, Comparative Investigation of Rotary and Linear Motor Feed Drive Systems for High Precision Machine Tools}, AMC2000 - IEEE, Nagoya, 2000.

[8] Sang-Moon Hwang, Geun-Bae Hwang, Weui-Bong Jeong and Yoong-Ho Jung, Cogging Torque and Noise reduction in Permanent Magnet Motors by Teeth Pairing, IEEE, 2000.

[9] Rusli, M., Moscrop J.,Cook C. and Platt D., An Analytical Method for Predicting Cogging Forces in Linear Induction Motors, Proceeding of 8th LDIA conference, Netherland, 3-6 july 2011.

[10] Sung Whan Youn, Jong Jin Lee, Hee Sung Yoon, and Chang Seop Koh, **A New Cogging-free Permanent-magnet Linear Motor**, IEEE Transactions on Magnetics, Vol. 44, No. 7, July, 2008.

[11] Xu, W., Zhu, J., Tan, L., Guo, Y., Wang, S., Wang, Y., Optimal Design of a Linear Induction Motor Applied in Transportation, IEEE, 2009.

[12] __,Cedrat Inc., CAD Package for electromagnetic and Thermal Analysis using Finite Elements, CEDRAT Copyright, July 2007.

[13] Kumin, L, Stumberger, G., Dolinar, D., and Jezernik, K., Modeling and Control Design of a Linear Induction Motor, ISIE'99, IEEE, Bled, Slovenia, 1999.

[14] Zhu, Z.Q., Xia, Z.P., Howe, D., Mellor, P.H., Reduction of Cogging force in slotless linear permanent magnet motors, IEE Proc.-electr. Power Appl., Vol 144, 4 July 1997.

[15] E. R. Laithwaite, and S.A. Nasar, Linear-Motion Electrical **Machines**, Proceedings of IEEE, Vol. 58, No. 4., April 1970.

[16] B. T. Ooi, **A Generalized Machine Theory of Linear Induction Motor**, Presentation paper on PES Winter Meeting, New York, 1973.

[17] Cruise, R.J., and Landy, C. F., Reduction of Cogging Forces in Linear Syncronous Motors, IEEE, 1999.

[18] Liu, J., Lin, F., Yang, Z., Zheng, T. Q., Field Oriented Control of Linear Induction Motor Considering Attraction Force & End-Effects, IEEE, 2006.

[19] Philip L. Arger, Induction Machines, Gordon and Breach Science Publishers, New York, 1961.

[20] S. Nonaka, and T. Higuchi, **Elements of Linear Induction Motor Design**, IEEE Transactions on Magnetic, Vol. MAG-23, No. 5, September 1987.

ACKNOWLEDGMENT

The author would like to thank to the Directorate general of high education of the Cultural and educational ministry of Republic of Indonesia in related to financial supporting for completing this research project and the School of Mechanical, Materials and Mechatronic Engineering, Faculty of Engineering, University of Wollongong which has provided the research facilities and finite element software and The University of Brawijaya which has encouraged for completing this research project.

Mochammad Rusli was Completing the under graduate at the Institut technology Sepuluh Nopember Surabaya on 1986, and Master program for Dipl.-Ing. At the Techniche Universitaet Braunschweig Germany on year 1996. Now he is as PhD postgraduate student at the University of Wollongong Australia with research interest reducing cogging effects by improving design procedure and implement control strategies in linear induction motor.