KIEE International Transactions on Electrical Machinery and Energy Conversion Systems, Vol. 5-B No. 2, pp. 137~141, 2005 **137**

Design of PM Excited Transverse Flux Linear Motor of Inner Mover Type

Do-Hyun Kang†, Jong-Bo Ahn*, Ji-Won Kim*, Jung-Hwan Chang* and Soo-Jin Jung**

Abstract - A transverse flux, PM-exited linear motor (TFM-LM) with inner mover was designed and built. Its output power density is higher and its weight is lower than those of the conventional PM exited linear synchronous motors (PM LSM).
To obtain the maximum thrust force under the given volume, the thrust force density with respect to the ratio of the slot width and the length of pole pitch is analyzed by the 3-dimension finite element method (FEM). Finally, calculated static thrust forces was compared with the experimental values.
The calculated and measured performance of the transverse flux, PM-exited linear motor with inner mover revealed great potential for system improvements by reducing the mass of the linear motor. For examples, when this motor was applied to a ropeless elevator, it was possible to increase the power density by more than 400% over the conventional PM-LSM. The results of this study recommend this type of motor for the ropeless elevator or gearless direct linear driving system.

Keywords: transverse flux, PM-excited, linear motor, finite element method, high power density.

1. Introduction

According to the recent development of power electronic devices (GTO, IGBT), materials (permanent magnet, super conductor), and design technology, new types of electrical machines are beginning to emerge.

A novel electrical machines, based on the new concept of transverse flux configuration, lead simultaneously to a considerable increase in the power density and efficiency.

The topological investigations regarding magnetic circuit geometry and winding configuration of the transverse flux machines have brought up a variety of constructing arrangements with different features for several types of application, e.g. [1]. Here, the PM-exited linear motor with inner mover, based on the transverse flux configuration, leads to a considerable increase in power density for the moving part.

When the proposed motor of this study is used in a ropeless elevator, it is possible to increase power density more than 400% over comparing with the equivalent, conventional, PM-LSM. The result of this study can be utilized for development of a ropeless elevator or gearless, linear moving system with high output.

† Corresponding Author: KERI PO Box 20, Changwon, Kyungnam 641-120, Korea(dhkang@keri.re.kr)
* KERI PO Box 20, Changwon, Kyungnam 641-120, Korea
** LG INNOTEK Motor Research Department #978-1, Jangduk-dong, Gwangsan-gu, Gwangju-city 506-731, Korea
Received April 13, 2004 ; Accepted April 20, 2005

2. Configuration and Principle OF THE TFM-LM

Fig. 1 presents a general view of the TFM-LM; the view with long primary configuration and the principles of force generation are shown in Fig. 2. The passive back irons are cut and developed to demonstrate the principles of force generation. The magnetic polarities between movers N and, S, and stators N_1, N_2, N_3, S_1, S_2 and, S_3 generate the total traction force F_T in one direction. The TFM-LM uses the PMs as excitation. The magnetic flux density in the air gap can be amplified, because the flux-producing area of the PM is bigger than the stator pole width in the air gap. The great advantage of the TFM-LM with inner mover is the system improvements that result from reducing the mass of the mover. Similar to the switched reluctance motor drives, the TFM-LM has the traction force ripple, which has limited its use in some applications. This force ripple could be minimized by controlling the current shape, [2]-[3].

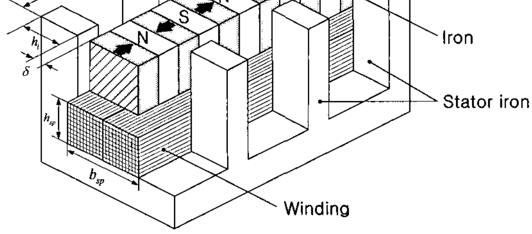


Fig. 1 Basic configuration of TFM-LM

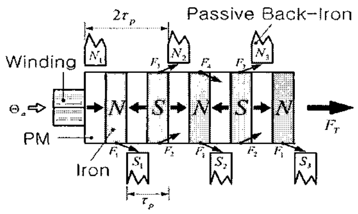


Fig. 2 Principles of force generation

From the configuration of the TFM-LM, the extracted one-dimensional model and the magnetic equivalent circuit for the magnetic flux path are shown in Fig. 3. This model and the corresponding magnetic equivalent circuit, where the saturation and stray magnetic flux component are ignored, are the starting point in developing a procedure for analytical calculation of the traction force. Θ_m and Θ_a are magnetomotive force by PM and magnetomotive force by primary winding, respectively [4].

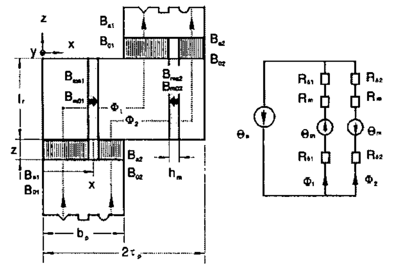


Fig. 3 One-dimensional computational model and magnetic equivalent circuit of TFM – LM

The traction force produced in TFM-LM can be explained using the magnetic coenergy conversion. The magnetic energy W_m, and the magnetic coenergy W_{co}, stored in the magnetic fields are as follows, [5]:

$$W_m = \int_V \int_0^B H(B) dB dV \quad (1)$$

$$W_{co} = \int_V \int_0^H B(H) dH dV \quad (2)$$

In terms of coenergy, the expression for the traction force is:

$$F_x(x) = \left[\frac{\partial W_{co}}{\partial x}\right] \quad (3)$$

The magnetic coenergy W_{co} is from (2):

$$W_{co} = \frac{2zh_i}{2\mu_0}\left[B_1^2\left(x - \frac{h_m}{2}\right) + B_2^2\left(b_p - x - \frac{h_m}{2}\right)\right] + W_{co1} + W_{co2} \quad (4)$$

W_{co1}, W_{co2} are the shares of magnetic coenergy in magnets and are given by:

$$W_{co1} = \frac{B_{m1}^2}{2\mu_0\mu_m} h_m h_i l_r \quad (5)$$

$$W_{co2} = \frac{B_{m2}^2}{2\mu_0\mu_m} h_m h_i l_r \quad (6)$$

The magnetic flux densities in the PM area, B_{m1} and B_{m2}, are:

$$B_{m1} = B_1 \frac{(x - h_m/2)}{l_r} \quad (7)$$

$$B_{m2} = B_2 \frac{(b_p - x - h_m/2)}{l_r} \quad (8)$$

Thus the traction force F_x is obtained from (3) and (4):

$$F_x = -\frac{4zB_a B_0}{\mu_0} \cdot h_i \quad (9)$$

In (9) B_a is magnetic flux density in the air gap excited by the primary winding, and B_0 is the magnetic flux density in the air gap excited by the PM.

The traction force density F_{xd} can be derived by dividing (9) by $2\tau_p$. $2h_i$, [6],[7]:

$$F_{xd} = B_0 \frac{\Theta_a}{2\tau_p} \quad (10)$$

The traction force density F_{xd} is proportional to the magnetomotive force Θ_a and the magnetic flux density in the air gap B_0 and is inversely proportional to the pole pitch τ_p Thus, the initial data required to derive a basic design for a TFM-LM are: Θ_a, τ_p, h_{sp}, δ, h_i, b_{sp}.

3. Design Elements of a Ropeless TFM-LM compared with a Linear PMSM

An industrial application of the previously presented machine is a TFM-LM dedicated for ropeless elevators. So, for comparative reasons with a 3 kW linear PMSM, [8], used also for ropeless elevators and presented in TABLE 1, the initial data required to derive the basic design for such a type of TFM-LM are:

$$\Theta_a = 10\text{ kA} \qquad \tau_p = 50\text{ mm} \qquad h_{sp} = 40\text{ mm}$$
$$\delta = 5\text{ mm} \qquad h_i = 40\text{ mm} \qquad b_{sp} = 65\text{ mm} \quad (11)$$

Table 1 Specifications of the Linear PMSM

Parameters		Values	Units
Force [N]		3,000	speed 1[m/s] acceleration 1[m/s^2]
Power [kW]		3	-
Total mass [kg] (primary +moving part)		469	kg/m
Moving mass[kg]		270	max. load: 140 kg car mass: 130 kg
Primary	length [mm]	3,055	-
	width [mm]	150	-
	height [mm]	90	-
Moving part	mass [kg]	36	-
	No.of poles	16	-
	length [mm]	1,000	-
	height [mm]	150	-
	width [mm]	30	-
Thrust force/ mass	moving part [N/kg]	6.4	-
	Total [N/kg]	83.3	-
Airgap length [mm]		5	-
Efficiency		0.62	-
Power factor		0.91	-
Force density [kN/m^2]		10	-

Thus, presuming an usual ratio of $\tau_p/\delta \approx 10$, respective of $\Theta_a/\delta \approx 1{,}000$AT/mm, it is possible to obtain, for the values of τ_p = 50mm and Θ_a = 10,000AT (saying Θ_a = 15,000AT for the case of overloading), the required condition for acquiring the maximum value for the thrust force density.

Table 2 Specifications of THE TFM-LM for Ropeless Elevator

Parameters		Values	Units
Thrust force [N]		3,000	speed 1 [m/s], acc. [m/s^2]
Power [kW]		3	-
Total mass [kg]		107.84	related to1m of length
Moving mass [kg]		270	load: 140 kg, car: 130 kg
Primary	length [mm]	3,055	-
	width [mm]	215	-
	height [mm]	200	-
	τ_p [mm]	50	-
	b_p [mm]	40	-
	h_{sp} [mm]	40	-
	b_{sp} [mm]	65	-
Moving part	mass [kg]	10.3	-
	length [mm]	317	-
	height [mm]	75	-
	width [mm]	55	-
	h_m [mm]	20	-
Force/ mass	total [N/kg]	27	-
	Mov.part [N/kg]	291	-
Airgap length [mm]		5	-
MMF [AT]		10,000	-
Force density [kN/m^2]		63	-

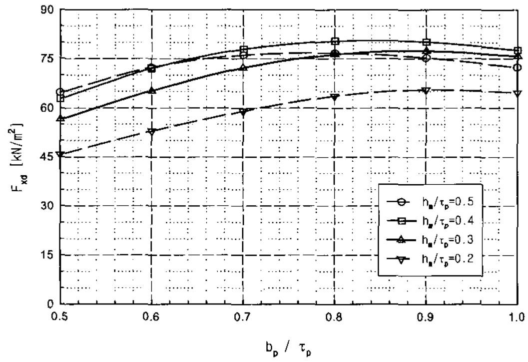


Fig. 4 Force density due to h_m and b_p

So, Fig. 4 shows the obtained variation of the thrust force density due to h_m and b_p. For the magnet height of h_m = 20 mm and for the pole width of b_p = 40 mm (meaning h_m/τ_p = 0.4, respective b_p/τ_p = 0.8) it is possible to obtain the maximum value for a thrust force density of 80 kN/mm^2 (see also Fig. 4).

Using these initial inputs, the resulted value for the traction force density for the TFM-LM is F_{xd} = 63 kN/m^2, which is approximately six times higher than the ordinary force density of the corresponding 3 kW, PM-LSM (see also Table 1 and Table 2).

By a magnetostatic, 3D FEM analysis it was possible to find the maximum value of the thrust force density of the before mentioned 3 kW TFM – LM, with the respect of ratio of the pole width, respectively of the magnet height to the length of the pole pitch.

4. A Scaled-Down Model OF THE TFM-LM

4.1 Construction of the TFM-LM model

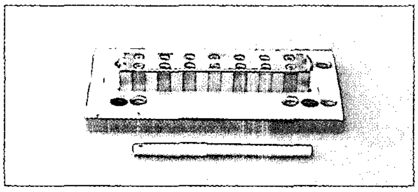
The photos from Fig. 5 depict the scaled-down mover and the stator; TABLE III contains the basic specification of the scaled-down model.

Table 3 Basic Specifications of the TFM-LM Mod el

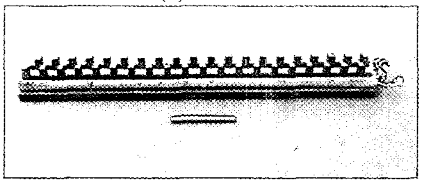
Parameters	Values	Units
Airgap (δ)	1mm	-
Polar pitch (τ_p)	20mm	-
PM height (h_m)	10mm	h_m/τ_p = 0.5
Pole width (b_p)	14mm	b_p/τ_p = 0.7

Pole length (h_l)	20mm	-
Height of window (b_{sp})	20mm	-
Width of window (b_{sp})	30mm	-
Stator	70×65x800mm^3	-
Mover	28×20x150mm^3	-
Conductor	1×3mm^2	-
Turns number	78×2	-
Windows space factor	0.6	-

The used NdFeB PMs have residual magnetic flux density of B_r = 1.2 T and relative magnetic permeability of μ_r = 1.05



(a) Mover



(b) Stator

Fig. 5 The scaled-down model of the TFM-LM

4.2 Experimental tests & results

We analyzed the scaled-down TFM-LM model with 3D finite element method. The results of the numerical analysis are presented in Fig. 6, and they are compared with the measured values on the TFM-LM scaled-down model. The maximum error between the measured data and the 3D FEM calculation showed 23.6% for 1,000 AT, 20.45% for 2,000 AT, 20.4% for 3,000 AT and 14.4% for 4,000 AT.

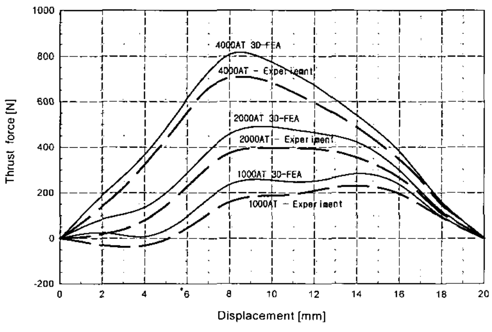


Fig. 6 Calculated vs. measured thrust force of the experimental TFM-LM model

Fig. 7 indicates the variation of the force density, F_{xd}, with the magnetomotive force, Θ_a, related to the experimental data and FEM analysis (3D calculation). The maximum error in force density between measured data and the FEM calculation result showed 28.8% for 1,000AT 24.6% for 2,000 AT, 19.6% for 3,000 AT and 14.4% for 4,000 AT. Under these circumstances, it is essential to reconsider the design data for the initial proposed 3 kW ropeless TFM-LM. Table 4 presents the final specification of the ropeless TFM-LM. It is to be noted here that the thrust force density value is 44.8 kN/m^2.

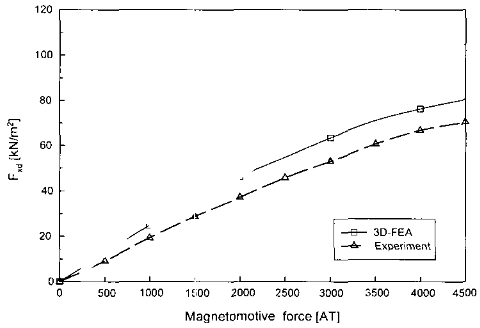


Fig. 7 Force density due to MMF of the experimental model

The results achieved permit a comparision between the two considered 3 kW ropeless motors: the linear PMSM and the TFM-LM. The TFM-LM presents a 4 times higher thrust force density than the equivalent PM-LSM regarding the mass of the motor and a 2.5 times higher thrust density force regarding the mass of the mover only.

Table 4 Final Specs. of the designed TFM-LM

Parameters		Values	Units
Total mass [kg] (primary +moving part)		112	kg/m
Moving part	mass [kg]	10.3	-
	length [mm]	317	-
Thrust force/mass	total [N/kg]	26.8	-
	moving part [N/kg]	206.9	-
Thrust force density [kN/m^2]		44.8	-

5. Conclusions

Based on a proposed one-dimensional, computational linear model and the correspondent equivalent magnetic circuit, an analytical calculation procedure of the thrust force of a TFM-LM was developed. An application for a 3 kW ropeless TFM-LM was performed.

For optimizing the design of such a machine, an experimental scaled-down model of the before mentioned TFM-LM and also the correspondent 3D FEM computational model were derived.

Finally, a comparative study with the existing equivalent 3 kW ropeless PM-LSM was carried out. Thus, it is to be noted here that the TFM-LM design variant presents a 4 times higher thrust force density than the equivalent PM-LSM regarding the mass of the motor and a 2.5 times higher thrust force density regarding the mass of the mover only.

References

[1] H.Weh: "Ten years of research in the field of high force density transverse flux machines", Symposium on Power Electronics, Industrial Drives, Power Quality, Traction Systems, A3 pg. 1-8, Capri, 1996.

[2] R. Krishnan: "Switched reluctance motor drives", CRC Press, 2001.

[3] L.A.P. Henriques, L.G.B. Rolim, W.I. Suemitsu, P.J. Branco: "Torque ripple minimization in a SR drive by neuro-fuzzy compensation", IEEE Transactions on magnetics, vol. 36, no. 5, Sept. 2000.

[4] H.Weh: "Transverse flux machines in drive and generator application", IEEE Conference Power Tech, 1955, June, 13-22, Stockholm.

[5] S. A. Nasar: "Electromagnetic energy conversion device and systems", Prentice-Hall, Inc. 1970.

[6] D. H. Kang: "Transversalflussmaschinen mit permanenter Erregung als Linearantriebe im schienengebundenen Verkehr", Dissertation, TU Braunschweig, 1996.

[7] D.H. Kang, H. Weh: "A study of the design of linear motor with transverse flux configuration for rail traction system", The Transactions of the Korean Institute of Electrical Engineers, vol. 6, pg. 301-308, 1999.

[8] J. F. Gieras, Z. J. Piech: "Linear Synchronous Motors", CRC Press LLC, 1999.

Do-Hyun Kang

He was born in Busan, Rep. of Korea in 1958. He received B. S. Degree in 1981 and M. S. Degree in 1989 in electrical engineering from the Hanyang University, Seoul, Rep. of Korea and the Dr. -Ing. Degree in 1996 in Institute of Electric Machines, Traction and Drives from Technical University Braunschweig, Braunschweig, Germany. He worked as Design Engineer in Nuclear Power Plant at Hyundai Construction Co. from 1981 until 1986. He is the Director of Mechatronics Research Group of Korea Electro-technology Research Institute. His research interests are magnetic levitation, linear drives, new electric machines.

Jung-Hwan Chang

He was born in Busan, Rep. of Korea in 1968. He received B. S. and M.S. degrees in electrical engineering and Ph.D. degree in precision mechanical engineering from Hanyang University, Seoul, Rep. of Korea in 1994, 1997 and 2001, respectively. From 2001 to 2002 he worked at Institute of Brain Korea 21 at Hanyang University, where he developed micro drive and high-speed spindle motor. From 2002 to 2003, he worked as research fellow at University of California at Berkeley with the support of Korea Science and Engineering Foundation, and he analyzed and developed electrically controlled engine valve system. He is currently working in Korea Electrotechnology Research Institute (KERI) as a senior researcher. His interests are the design and analysis of electro-mechanical systems including driving circuits.

Jong-Bo Ahn

Jong bo Ahn was born in 1961, He received B.S. degree, M.S. degree, and Ph. D degree in electrical engineering from Seoul National University, Seoul, Korea, in 1986, KAIST, Daejon, Korea, in 1995, and Pusan National University, Busan, Korea, in 2005, respectively. He worked as senior researcher at Echeon Electric Co. from 1986 to 1996. He is Team leader of Mechatronics Research Group of Korea Electrotechnology Research Institute.

Tel : 055-280-1478, Fax :055-280-1547

Ji-Won Kim

Ji Won Kim was born in 1971, He received B.S. degree and M.S. degree in Control and Instrumentation engineering from the National of Seoul, Seoul, Korea, in 1994 and Kwangwoon University, Seoul, Korea, in 1996, respectively. He is the senior researcher of Mechatronics Research Group of Korea Electrotechnology Research Institute.

Tel : 055-280-1335 Fax : 055-280-1547

Soo-Jin Jung

Soo Jin Jung was born in 1974, He received B.S. degree and M.S. degree in electrical engineering from the Yeungnam University, Kyeongsang province, Korea, in 2001, 2003, respectively. He worked as researcher of Mechatronics Research Group of Korea Electrotechnology Research Institute from 2001 to 2004. He is researcher of LG Innotek Corporation.

Tel : 055-280-1487, Fax: 055-280-1547