Journal of Engineering and Applied Sciences 11 (8): 1752-1761, 2016
ISSN: 1816-949X

A Review of Permanent Magnet Linear Motor with Halbach Array

[1]A.K.M. ParvezIqbal, [1]F.A.M Mokhtar, [1]K.S.M. Sahari and [2]Ishak Aris
[1]Centre for Advanced Mechatronics and Robotics, College of Engineering,
Universiti Tenaga Nasional (UNITEN), Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[2]Department of Electrical Engineering, Faculty of Engineering,
Universiti Putra Malaysia (UPM), 43400 UPM Serdang, Selangor, Malaysia

Abstract: Utilizing Halbach magnet array, magnetic flux can be built up on the strong side of the array while the flux cancelled on the other weak side. Inherently, rotor of rotary motor has infinite rotational length with respect to its rotation while mover of the linear motor has finite length with respect to mover's translation. This study starts with a brief introduction of Halbach array and its method in designing linear motors. It then discusses the difference between conventional permanent magnet array with Halbach array and also the difference between slotted type and slotless Halbach array. This study has reviewed the implementation of Halbach array in machines with different topologies and the Halabch magnetization field distribution.

Key words: Linear motor, finite element methods, FEM, PM, Halbach array, permanent magnet linear motor

INTRODUCTION

Halbach magnet array was proposed by Klaus Halbach in 1980 when discovered an interesting permanent magnet configuration that concentrates magnetic flux on one side of the array and cancels it on the other side (Halbach, 1980). By superposition, magnetic flux is constructed on one side of the magnet of which magnetization direction rotates continuously while the flux is destructed on the other side. Halbach magnet array is widely employed in electric motor as the coil become denser because of exposed of magnetic flux density. The more magnetic flux is exposed to the coil, the more actuating force of the motor is produced by Lorentz force. The ideal array of Halbachis resembled with segmented magnet hence, the continuously rotating magnetization is difficult to manufacture (Lee *et al*., 2004). The linear motorwith Halbach array can be constructed with either axially magnetized or radially magnetized mover.

Magnetic flux of Halbach magnet array can be enhanced on one side (strong side) of the array while the flux cancelled on the other side (weak side). If Halbach magnet array is used in electric motor, magnetic flux density exposed to coil becomes denser. Generally non-linearity is detrimental to position control the motor. The force ripple is non-linearity characteristics of electric motor. The more magnetic flux is exposed to the coil, the more actuating force of the motor is produced by Lorentz force. If the motors can generate more actuating force, they can move more rapidly. If the motors have no slot, cogging force ripple will not be generated. Hence, the electric motor with Halbach magnet array can satisfy needs of high precision positioning linear motor that is used in high precision manufacturing of semiconductor industry (Kim *et al*., 1997).

In particular, the Halbach magnetized mover has inherent self-shielding property and thereby does not require a back iron. Likewise, the axially magnetized mover does not need one for the magnetic path while the radially magnetized mover comprises array surface-mounted magnet blocks on an iron backing. Moreover, the fundamental field of the Halbach array is stronger than that of a conventional array and thus the power efficiency of the motor with Halbach array is doubled. The magnetic field of the Halbach array is more purely sinusoidal than that of the others, thus caused by a simple control structure (Wang and Howe, 2005). These advantages are consider the Halbach array particularly appropriate for linear machines.

This study reviews alternative of Halbach linear topologies and compares the performance of Halbach array with conventional permanent type. This study also describes the slotted and slotless topologies of Halbach array in desiginglinear motor. Finally the application of Halbach arrayin linearmotor, generator and high speed gear are discussed.

Corresponding Author: A.K.M. ParvezIqbal, Centre for Advanced Mechatronics and Robotics, College of Engineering, Universiti Tenaga Nasional (UNITEN), Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia

MATERIALS AND METHODS

Halbach design

Magnetic field of Halbach: In ideal Halbach array, the magnet lies between z = 0 and z = d and suppose the width of block is enough large as shown in Fig. 1, φ_1-φ_3 and are scalar magnetic potentials of three regions. Vertical and horizontal components of magnetic field are considered. Ideal Halbach array hasmagnetization as the follow:

$$M_y = M_0 \sin(ky)$$
$$M_z = M_0 \sin(ky)$$
$$M_x = 0$$

Where:

k = The wave number
$k = 2\pi\lambda$, λ = Wave length of Halbach array
M_0 = Related to the B_r
$M_0 = B_r/\mu_0$, B_r = Remanence

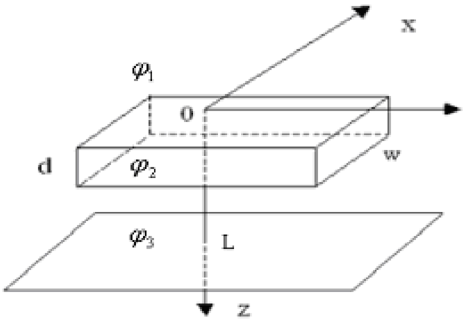


Fig. 1: Magnet and the coordinate

The vertical and horizontal components of magnetic field have the similar characteristics, therefore only one component is taken into account. Horizontal and vertical components are all changing along the array sinusoidally as the amplitude of sine waves can indicate the characteristics of Halbach array. The magnetic field equation of the Halbach array is expressed as follows:

$$B_0 = B_r[1 - e^{-kd}]\frac{\sin\left(\frac{\pi}{m}\right)}{\left(\frac{\pi}{m}\right)}$$

when z>0, the equations are expressed as follows:

$$B_m = B_r[1 - e^{-kd}]e^{-kz}\frac{\sin\left(\frac{\pi}{m}\right)}{\left(\frac{\pi}{m}\right)}$$

$$B_y = B_m \sin(ky)$$
$$B_z = B_m \cos(ky)$$

Where:

k = The wave number
B_r = Remanence
m = The number of magnets per spatial wave length

This ideal Halbach magnetization is self-shielding in the permanent magnet and produce sinusoidal airgap filed distribution as shown in Fig. 2 (Trumper *et al*., 1996).

Ideally, a Halbachmagnetized cylinder structures would be created from an infinite length cylinder of

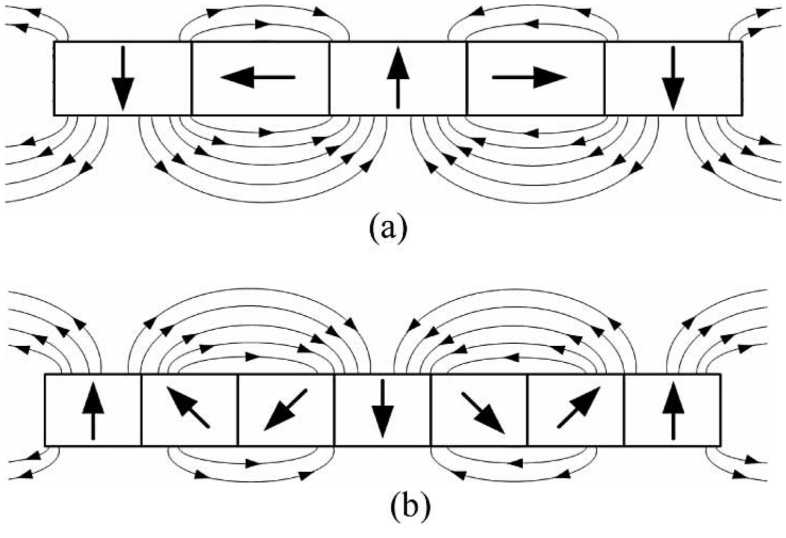


Fig. 2: Halbach PM arrays: a) two segments per pole and b) three segments per pole

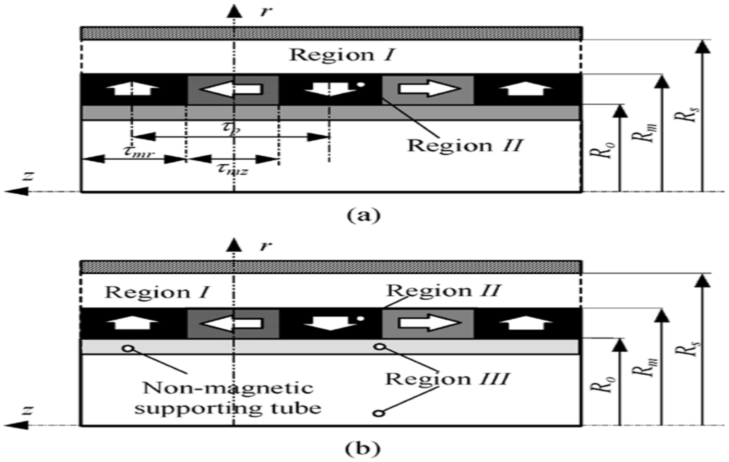
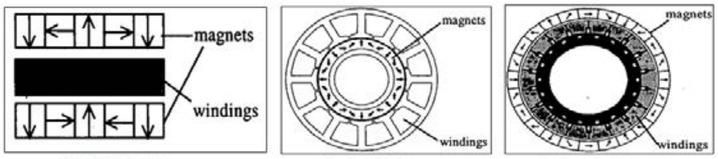
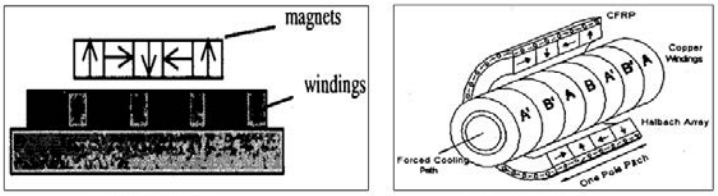


Fig. 3: Field regions: a) Ferromagnetic tube and b) Nonmagnetic tube



Axial Field structure Slotted radial-field motor Slotless radial-field motor



Planar Linear Motor Tabular Linear Motor

Fig. 4: Different topologies of liner motor with Halbach array

magnetic material with continuously varying direction of magnetization of magnetic field. The cylinder composed of ferromagnetic material producing an intense magnetic field and confined entirely inside with zero field outside. Advanced rare earth NdFeB magnets have high residual strength which enhance the magnetic forces. Besides, strong coercive forces which reduce the demagnetizing effect and are very stable under higher working temperatures (Trumper *et al*., 1996; Reitz *et al*., 1993; Moon, 1984; Lee *et al*., 1997; Jang, 1997; Campbell, 1994; Zhu and Howe, 2001; Jian and Chau, 2010; Qi *et al*., 2011; Dwari and Parsa, 2011; Praveen *et al*., 2012).

For linear permanent magnet machines, the active number of poles does not have to be an even number.For a given number of pole pairs, different slot/pole number combinations lead to different winding factors for both the fundamental and high-order EMF harmonics and for the armature reaction magnetomotive force distribution. Further, the cogging torque due to slotting is approximately related to the inverse of the smallest common multiple of poles. Thus, the choice of a particular slot/pole combination has a significant influence on the performance, demagnetization withstand capability and noise/vibration characteristics of a motor. If the permeability of the ferromagnetic supporting tube may be assumed to be infinite, only two field regions are considered: the air-gap region I and the permanent magnet region 2 as shown in Fig. 3 (Wang and Howe, 2005).

Topologies of Halbach linear motor: The structure of halbachlinear motor are important as an approximate design may produce widely higher force density but may also produce an undesirable destabilizing tooth ripple cogging force with the highest eddy current loss in the magnets and the iron, during high speed operation. There are various possible Halbachmagnetized permanent magnet machine topologies such asslotted and slotless, radial and axial-field, rotary and linear as illustrated in Fig. 4 (Lee *et al*., 2004).

One of the disadvantages faced in the slotted motor design is cogging effect as it causes a ripple in the torque generated by the motor (Zhu and Howe, 2001). The cogging effect is produced by the interaction between the rotor magnetic flux and the variation of stator reluctance caused by slotting. Cogging torque is caused by the variation of the magnetic energy stored in the air gap which is resulted from the angular position of the rotor. A slotless motor design on the other hand, eliminates the tooth ripple component of cogging and also produces very little slot harmonic effects thereby facilitating the production of smooth output torque required for the application. However, the output torque generated by the slotless motor is low compared to that by an equivalent slotted one due to its large air gap (Shao *et al*., 2013; HO *et al*., 2015; Jin *et al*., 2015; Zhang *et al*., 2015; Li *et al*., 2014; Liu *et al*., 2014; Jing and Zhang, 2013; Shen and Zhu, 2013; Xu *et al*., 2016).

Figure 5 is shown that slotless tubular PM actuators using quasi-Halbach magnetization patterns have a number of attractive characteristics, such as a sinusoidal back-electromotive force (back-EMF) waveform which produces a very low electromagnetic force ripple and very low cogging force. Due to the “self-shielding” magnetization characteristics of Halbacharray, the magnetic flux which passes through the core is relatively weak (Meessen *et al*., 2011; Praveen *et al*., 2012).

On the other side, conventional iron-cored permanent magnet motor can be designed to have a high efficiency; the no-load iron loss with significant high rotational speeds. In addition, unbalanced magnetic pull, both on no-load and full-load may impose excessive force/stiffness requirements on the bearing system. An aircored rotor with slotless stator Halbach machines overcome these problems while still offering a relatively high power density.

Figure 6 and 7 show the predicted result obtained by finite element analysis and measurement for air-cored and iron-cored Halbach magnetization motor, respectively. In air-cored machine the air-gap flux density varies significantly with the pole number. An optimal combination of the magnet thickness and the pole number of air-cored machine produces the maximum air-gap flux density. On the other hand the back iron of the iron-cored machine can enhance the air-gap field and electromagnetic torque by reducing the radial thickness of the magnet (Xia *et al*., 2004).

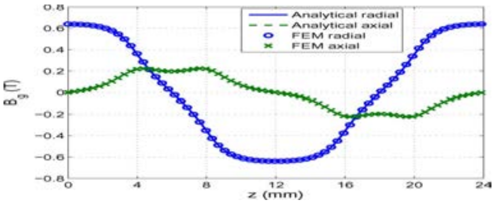


Fig. 5: The slot and slotless topologies flux density

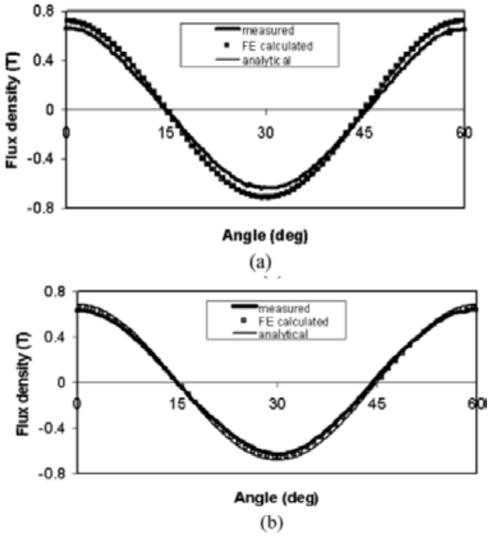


Fig. 6: Air-gap flux density distributions: a) Air-cored rotor and b) Iron-cored rotor

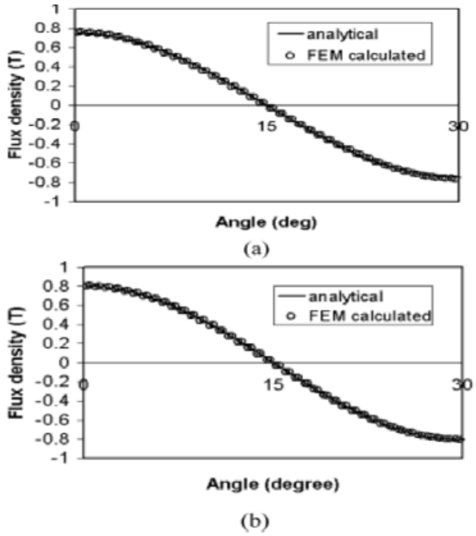


Fig. 7: Comparison of analytically and finite-element-predicted predicted field distributions for 12-pole, slotless, iron-cored, external Rotor Halbach magnetized magnet machine

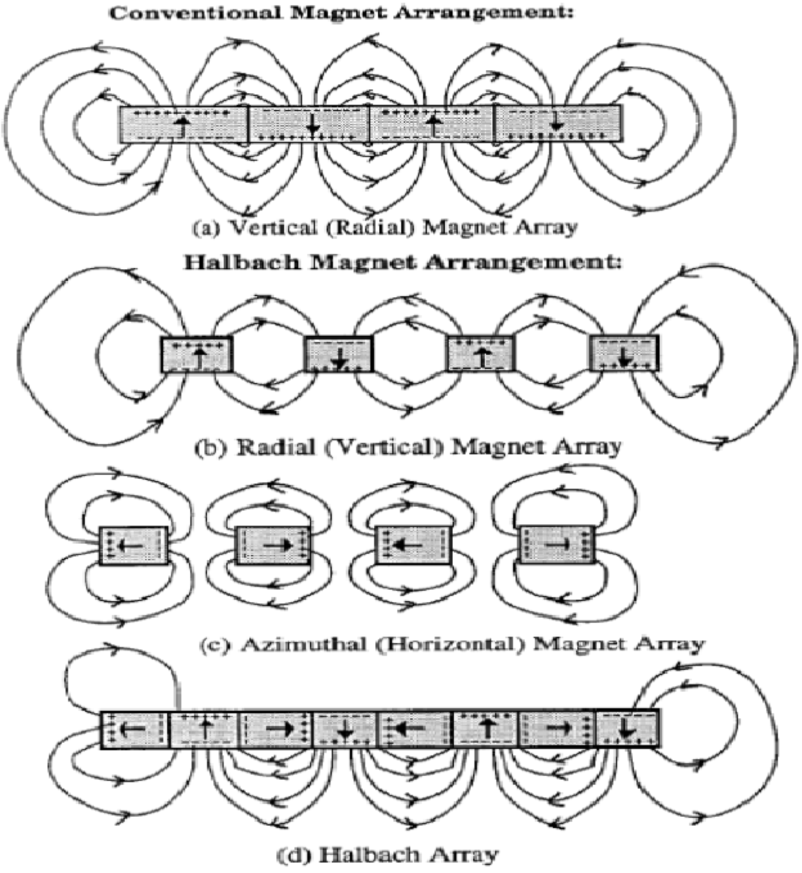
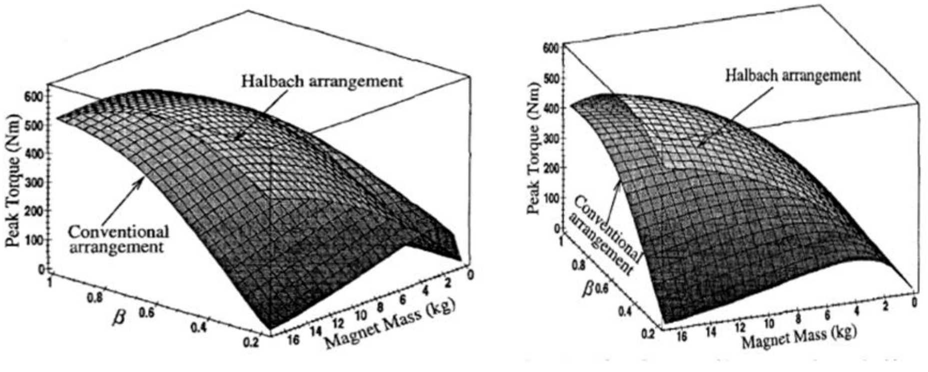


Fig. 8: Intuitive illustration of flux distribution in conventional and Halbach magnet arrays

RESULTS AND DISCUSSION

Comparison of Halbach array and conventional permenant magnet array: Halbach array models have one-sideness on discrete' where a magnetic block is being composed of paired magnetic charges. Magnetic fields emanate from positive magnetic charges and terminate on negative charges. Then, field lines from positive charges terminate on the closest "free" negative charge. This is the simple rule as conventional magnet array isconstructed, asshown in Fig. 8a. The field lines from the Halbach array are constructed via superposition. Firstly, magnet blocks separated into a radial (vertical for a linear motor) array and an azimuthal (horizontal for a linear motor) array as shown in Fig. 8b, c (Ofori-Tenkorrang and Lang, 1995). By applying the simple rules as mentioned above, one can easily construct the field lines for the individual arrays. The spatial flux distribution of the combined array is the sum of the flux distributions for the individual arrays. There is cancellation of field charges on one side of the array while on the other side of the array the field charges will be added. The radial array of magnets is applied to generate the rotational magnetization vectors either clockwise or counter clockwise while the azimuthal array of magnets is used to cancel the field charges. Figure 9 shows the comparison of the torque production capability of Halbach and conventional array of rotor magnet arrangements for a slotless armature. This shows that in conventional array a motor needsa back-op permeable to produces a higher torque, meanwhile, the Halbach arrangement always produces higher torquewithout a back-up permeable rotor. For a certain thickness of magnet, the Halbach array always produces higher torque as compare to the conventional array (Ofori-Tenkorrang and Lang, 1995; Saha *et al*., 2012; Liu and Garrett, 2005; Wakeland, 2000; Swift and Garrett, 2003).

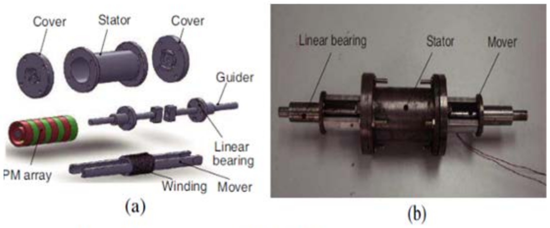
Application: The linear motors provide the better dynamic performance and higher reliability over conventional rotary-to-linear counterparts because of the absence of mechanical gears and transmission system. Among the



Achievable peak torques with magnetic rotor backing

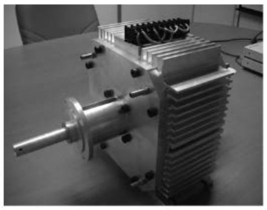
Achievable peak torques with non-magnetic rotor backing

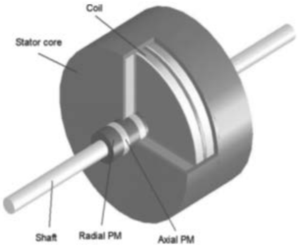
Fig. 9: The comparison of the torque production capability of Halbach and conventional rotor magnet arrangements



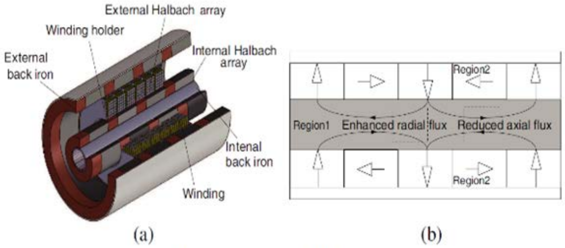
(a) (b)

The manufacturing parts of Halbach linear motor





Linear machine construction

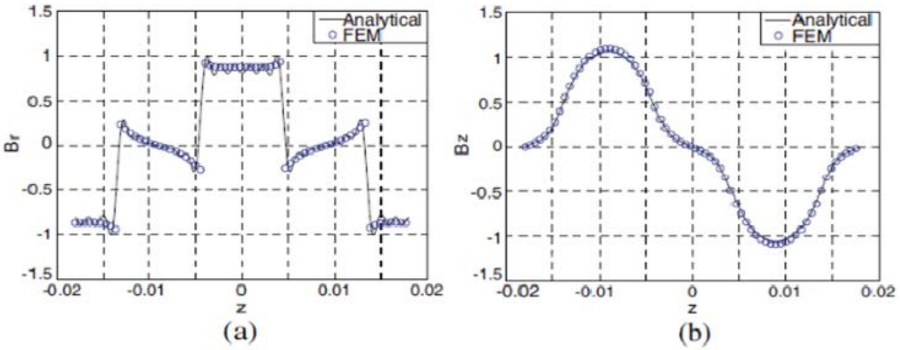


(a) (b)

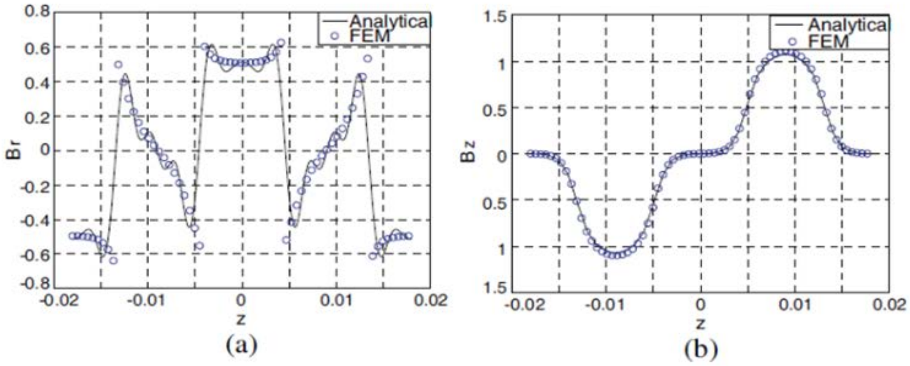
The structure of Dual Halbach array

Fig. 10: The various types of Fabricated linear motor with Halbach array

various linear machine topologies, tubular permanent magnet machines provide the highest efficiency; offer a high power/force density and excellent servo characteristics. A permanent magnetlinearmotor is a motor in which the motion goes in a straight line rather than in a circular motion. This type of motor is appropriate for applications that require motive force in a specific direction. Examples of ideal applications are printer heads and other types of office automation machines. Linear actuators can also be used for juicers, machines with pistons, systems to lock and unlock car doors and conveyor belts. In fact, there is an extremely wide range of products and applications for which a linear actuator is a great fit. Hence, linear permanent magnet machine are being used increasingly in application as varied as manufacturing automation, electrical power generation, transportation, healthcare and house hold appliances. Linear motors are also useful in the semiconductor fabrication and inspection processes. According to the application of liner motor it could be divided into two categories such as low-acceleration and high-acceleration linear motors. Low-acceleration linear motors are suitable for maglev trains and other ground-based transportation applications. Halbachlinear motors are normally rather short and are designed to accelerate an object to a very high speed. Figure 10 shows different types of linear motor with Halbach array.



Field variation at the centre of internal magnet area. (a)Variation of B_r (b) Variation of B_z



Field variation at the centre of external magnet area. (a)Variation of B_r (b) Variation of B_z

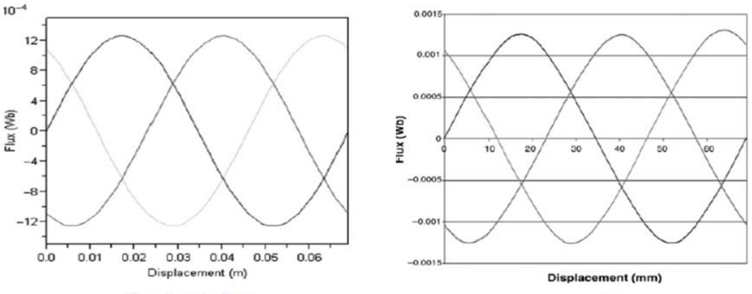
Fig. 11: Field variation at the centre of internal and external magnet area

Recent research introduces us to Dual Halbach array which proposes to enhance flux density in air gap and thus to improve output performance of linear machines. (Holmberg *et al*., 2003; Yan *et al*., 2013; Halbach, 1980; Choi and Yoo, 2008) magnetic field in three-dimensional space of a tubular linear machine with dual Halbach array is formulated based on Laplace's and Poisson's equations. In Fig. 10 magnet arrays with alternating magnetization directions are to produce radially directed flux density across the air gap of permanent magnet linear motor. It can not only increase the radial component of flux density which is important for axial force generation but also decrease the local force radial component which causes vibrations. Numerical result from Finite Element Method (FEM) is utilized to analyze and observe flux variation in three-dimensional space of the machine. It is a coordination of two Halbach arrays, especially with the same magnetization pattern for radially magnetized PMs and the opposite magnetization pattern for axial ones. This special arrangement can increase the radial component of magnetic flux density greatly in the air gap whereas reduces the axial flux density significantly. It indicates that the dual Halbach array may offer two advantages:

- The axial force can be improved much from the increased radial flux
- The radial force disturbance and vibration can be weakened from the decreased axial flux

For winding region, the mathematical model of the flux distribution is compared with both FEM and experimental results. For magnet region, the model is compared with FEM results as the probe cannot measure the flux field at this region. Magnetic field in either magnet region varies in line with the magnetization vector M. Therefore, the radial flux component is even-symmetric about z = 0 while the axial field is odd-symmetric. The radial flux density in the internal magnet area is greater than that in the external magnet area due to a decreasing section crossed by constant fluxlines as shown is Fig. 11 (Holmberg *et al*., 2003).

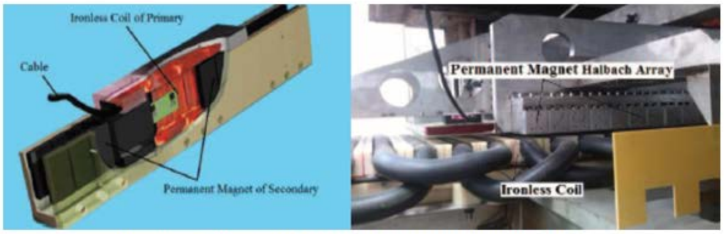
In many application of linear Halbach permanent magnet motor, the machine runs in a reciprocating linear motion while produces a linear three-phase output voltage. It is not a real three-phase output like in the rotary machine, since the machine runs forward and then moves backward after it reaches the end of the motion. A long-translator machine is the type selected for better overall performance as shown in Fig. 10. The governing



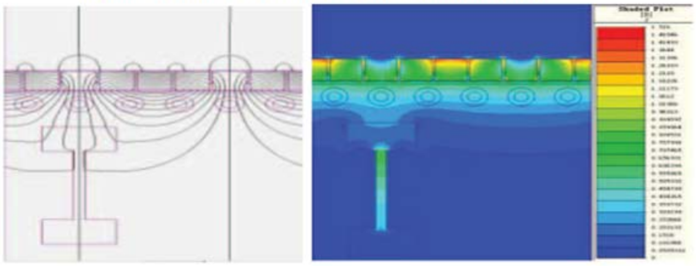
Three-phase flux linkages

Three-phase flux linkages of windings

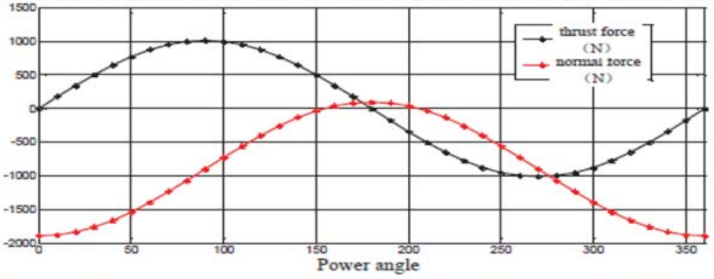
Fig. 12: Three-phase flux linkages



Structure of double sides ironless linear synchronous motor



Flux and flux density distribution when stator under magnet of vertical magnetization direction



Power angle characteristic when stator under magnet of vertical magnetization direction

Fig. 13: Double sided ironless synchronous liner motor and its magnetization and characteristic curve

equations are built with the following assumptions for simplification (Zhang *et al*., 2015; Wijono *et al*., 2010; Wang *et al*., 2001):

- First, the machine isanalysed without the stator slot. In the flux linkage calculation, the slots effect is usually incorporated by applying the Carter coefficient
- Then, the machine is assumed to be infinitively long and has a periodic construction
- The permeability of the stator core is assumed to be infinite whereas the relative permeability of the winding, air gap and permanent magnet as well as the shaft is assumed to be one

The flux linkages are plotted in Fig. 12 where flux linkage for all windings shows the three phase linear motor flux. Further, development in term of flux leakage of linear Halbach array is ironless permanent magnet linear synchronous motor which has advantages of low thrust fluctuation, highprecision positioning, high dynamic performance (Wang *et al*., 2001). This linear motor is widely used in low power application servo system. Flux leakage in linear statoris lees in horizontal magnetization direction compare to the vertical (Bianchi, 2000) as shown in Fig. 13 while bias amount of a negative DC is decreased a bit. Byusing the steel stator, attraction is greatly increased which reduces extra load.

CONCLUSION

Halbach array will be a favorable magnet design because of its self-shielding property and existence of distributed sinusoidal magnetic field in air gap. It is extensively used in linear motor system. The overall cost of Halbach array is lower than the conventional array in order to produce same amount of thrust. The impact is studied in comparison of different topologies of machines, their flux density and produced torque. In the future study, permanent linear magnet motor with dual Halbach array is proposed for further improvement of the magnetic flux density and thus increases the force output and displacement of mover. Dual Halbach arraycan minimize the volume of magnet array in linear motor. Halbach magnet arrays are a beneficial choice to reduce both the weightand the volume of the machine. It can also increase the magnetic flux density and therefore the torque output would be increased for ironless axial flux linear motor.

ACKNOWLEDGEMENTS

Researchers like to thank Kementerian Pendidikan Malaysia (KPM) and Fundamental Research Grant Scheme (FRGS) committee for funding this project and also to Universiti Tenaga Nasional for supporting this project.

REFERENCES

Bianchi, N., 2000. Analytical computation of magnetic fields and thrusts in a tubular PM linear servo motor. Poceedings of the 2000 IEEE Conference on the Industry Applications, October 8-12, 2000, IEEE, Italy, ISBN:0-7803-6401-5, pp: 21-28.

Campbell, P., 1994. Permanent Magnet Materials and their Applications. Cambridge University Press, New York, USA., pp: 74-75.

Choi, J.S. and J. Yoo, 2008. Design of a Halbach magnet array based on optimization techniques. IEEE. Trans. Magn., 44: 2361-2366.

Dwari, S. and L. Parsa, 2011. Design of halbach-array based permanent-magnet motors with high acceleration. IEEE. Trans. Ind. Electron., 58: 3768-3775.

Halbach, K., 1980. Design of permanent multipole magnets with oriented rare earth cobalt material. Nuclear Instruments Methods, 169: 1-10.

Ho, S.L., Q. Wang, S. Niu and W.N. Fu, 2015. A novel magnetic-geared tubular linear machine with halbach permanent-magnet arrays for tidal energy conversion. IEEE. Trans. Magnet., 51: 1-4.

Holmberg, D.G., G.S. Chen, H.T. Lin and A.M. Wo, 2003. Thermal modeling and performance analysis of a thermoacoustic refrigerator. J. Acoust. Soc. Am., 114: 782-791.

Jang, H., 1997. The compensation of torque ripple of brushless DC motor using feed-forward method. Master Thesis, Korea Advanced Institute of Science and Technology (KAIST), Korea.

Jian, L. and K.T. Chau, 2010. A coaxial magnetic gear with halbach permanent-magnet arrays. IEEE. Trans. Energy Conv., 25: 319-328.

Jin, P., Y. Yuan, Q. Xu, S. Fang and H. Lin *et al*., 2015. Analysis of axial-flux halbach permanent-magnet machine. IEEE. Trans. Magnet., Vol. 51, 10.1109/TMAG.2015.2449352

Jing, L.B. and Y.J. Zhang, 2013. Exact analytical method for magnetic field computation in the concentric magnetic gear with Halbach permanent-magnet arrays. Proceedings of the 2013 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), October 25-27, 2013,IEEE, Shanghai, China, ISBN:978-1-4799-0069-5, pp: 343-346.

Kim, W.J., D.L. Trumper and J.B. Bryan, 1997. Linear motor-leviated stage for photolithography. CIRP. Annal. Manuf. Technol., 46: 447-450.

Lee, M.G., D.G. Gweon and S.M. Kim, 1997. Modelling and optimum design of a fine actuator for optical heads. Mechatronics, 7: 573-588.

Lee, M.G., Lee, S.Q. and D.G. Gweon, 2004. Analysis of halbach magnet array and its application to linear motor. Mechatronics, 14: 115-128.

Li, D., R. Qu and Z. Zhu, 2014. Comparison of Halbach and dual-side vernier permanent magnet machines. IEEE. Trans. Magnet., 50: 801-804.

Liu, G., M. Shao, W. Zhao, Q. Chen and L. Mo, 2014. Cost reduction of a new fault-tolerant Halbach permanent magnet machine using ferrite magnet. IEEE. Trans. Magnet., 50: 1-4.

Liu, J. and S. Garrett, 2005. Characterization of a small moving-magnet electrodynamic linear motor. J. Acoust. Soc. Am., 118: 2289-2294.Meessen, K.J., B.L. Gysen, J.J. Paulides and E.A. Lomonova, 2008. Halbach permanent magnet shape selection for slotless tubular actuators. IEEE. Trans. Magnet., 44: 4305-4308.

Meessen, K.J., J.J.H. Paulides and E.A. Lomonova, 2011. Analysis of 3-D effects in segmented cylindrical quasi-Halbach magnet arrays. IEEE. Trans. Magnet., 47: 727-733.

Moon, F.C., 1984. Magneto-Solid Mechanics. John Wiley & Sons, New York, USA.,.

Ofori-Tenkorrang, J. and J.H. Lang, 1995. A comparative analysis of torque production in Halbach and conventional surface-mounted permanent-magnet synchronous motors. Proceeding of the Thirtieth IAS Annual Meeting, Industry Applications Conference, Oct. 8-12, Orlando, FL , USA, pp: 657-663.

Praveen, R.P., M.H. Ravichandran, V.S. Achari, V.J. Raj, G. Madhu and G.R. Bindu, 2012. A novel slotless halbach-array permanent-magnet brushless dc motor for spacecraft applications. Ind. Electron. IEEE Trans., 59: 3553-3560.

Qi, Z., P. Mengchun and C. Dixiang, 2011. Analytic calculation of magnetic field and force in Halbach permanent magnet linear motor. Proceedings of the 2011 10th International Conference on Electronic Measurement and Instruments (ICEMI), Vol. 4, August 16-19, 2011, IEEE, Hunan, China, ISBN:978-1-4244-8158-3, pp: 77-80.

Reitz, J.R., F.J. Milford and R.W. Christy, 1993. Foundation of Electromagnetic Theory. 4th Edn., Wesley, New York, USA., pp: 69-75.

Saha, C.R., P.H. Riley, J. Paul, Z. Yu and A.J. Jaworski *et al*., 2012. Halbach array linear alternator for thermo-acoustic engine. Sensors Actuat. A. Phys., 178: 179-187.

Shen, Y. and Z.Q. Zhu, 2013. General analytical model for calculating electromagnetic performance of permanent magnet brushless machines having segmented Halbach array. IET. Electr. Syst. Transp., 3: 57-66.

Swift, G.W. and S.L. Garrett, 2003. Thermoacoustics: A unifying perspective for some engines and refrigerators. J. Acoust. Soc, Am., 113: 2379-2381.

Trumper, D.L., W.J. Kim and M.E. Williams, 1996. Design and analysis framework for linear permanent-magnet machines. IEEE. Trans. Ind. Appl., 32: 371-379.

Wakeland, R.S., 2000. Use of electrodynamic drivers in thermoacoustic refrigerators. J. Acoust. Soc. Am., 107: 827-832.

Wang, J. and D. Howe, 2005. Tubular modular permanent-magnet machines equipped with quasi-Halbach magnetized magnets-part I: magnetic field distribution, EMF and thrust force. IEEE. Trans. Magnetics, 41: 2470-2472.

Wang, J., G.W. Jewell and D. Howe, 2001. Design optimization and comparison of tubular permanent magnet machine topologies. IEE Proc. Electric Power Appl., 148: 456-464.

Wijono, A. Arof and H. Ping, 2010. Analysis of magnetic field distribution of a cylindrical discrete halbach permanent magnet linear generator. IET Electric Power Appl., 4: 629-636.

Xia, Z.P., Z.Q. Zhu and D. Howe, 2004. Analytical magnetic field analysis of Halbach magnetized permanent-magnet machines. IEEE. Trans. Magnet., 40: 1864-1872.

Xu, L., G. Liu, W. Zhao, J. Ji and X. Fan, 2016. High performance fault tolerant halbach permanent magnet vernier machines for safety-critical applications. IEEE. Trans. Magnet., Vol. 52, 10.1109/TMAG.2016. 2524541

Yan, L., L. Zhang, T. Wang, Z. Jiao and C.Y. Chen *et al*., 2013. Magnetic field of tubular linear machines with dual Halbach array. Prog. Electromagnet. Res., 136: 283-299.

Zhang, Z., L. Shi, Q. Ge and Y. Li, 2015. Characteristics analysis of single-sided ironless linear synchronous motor based on permanent magnet Halbach array. Proceedings of the 2015 18th International Conference on Electrical Machines and Systems (ICEMS), October 25-28, 2015, IEEE, China, ISBN: 978-1-4799-8806-8, pp: 275-278.

Zhu, Z.Q. and D. Howe, 2001. Halbach permanent magnet machines and applications: A review. IEE. Proc. Electr. Power Appl., 148: 299-308.