Presentation of a Novel Transverse-Flux Permanent Magnet Linear Motor and Its Magnetic Field Analysis Based on Schwarz-Christoffel Mapping Method

Dongshan Fu, and Yanliang Xu

School of Electrical Engineering, Shandong University, Jinan 250061, China, xuyanliang@sdu.edu.cn

A novel transverse-flux permanent magnet linear motor (TFPMLM) named as double-sided double-excited one is proposed in this paper. Firstly, the operational principle and structural advantages of the TFPMLM are presented. Then, the 3-D magnetic circuit structure of the TFPMLM is simplified equivalently into a 2D one in order that Schwarz-Christoffel (SC) mapping method can be adopted to analyze the motor's magnetic field and characteristics. At last, The air-gap flux density distribution, back voltage and force waveforms when at no-load and at load are calculated by SC mapping method and 3-D FEM respectively for a prototyped linear motor, The results from the two methods coincide much better with each other.

***Index Terms*—Schwarz-Christoffel (SC) mapping, transverse-flux permanent magnet linear motor, 3-dimensional finite element method (3-D FEM).**

I. Introduction

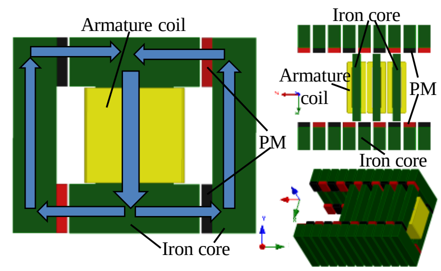
LINEAR motors, different from its counterpart rotary motor, can drive linear load directly, which as a result, enjoys excellent characteristics of high acceleration, high precision and high operating life. Transverse-flux permanent magnet linear motor (TFPMLM) benefits the additional advantages from the transverse-flux structure such as high ratio of force to weight, high fault tolerance and respective design of magnetic and electric loads, but normally suffers from the complex structure which leads to a heavy task to manufacture.

Due to its 3-D magnetic circuit structure, the TFPMLM is usually analyzed using 3-D FEM with high accuracy but also with time-consuming problem. 3-D magnetic network method is another method to be used to analysis the motor which consume a very short time but companies with low accuracy. The Schwarz-Christoffel(SC) mapping method is an another analytical method mainly to solve complex magnetic field of the motor[1], which can take into account not only the slotting effect but also the end effect and the magnetic flux leakage. However, the SC method is a 2-D one which may not be adopted directly to analyze TFPMLM.

In this paper, a novel TFPMLM with easy-manufacturing structure is proposed in Section II, and its magnetic field distribution and back voltage and force waveforms are performed by SC method in Section III, at last, in Section IV the results from SC method are verified by being compared with that from 3-D FEM.

II. The Presentation of the Novel TFPMLM

Fig. 1 shows the fundamental configuration of the proposed three-phase TFPMLM. It consists of armature section and field one, and the former, used as the mover, is constituted of many armature units, each of which is an I-shape iron core with a concentrated coil wrapped around it. The field section, used as the stator, is composed of two yoke plates located in two sides of the armature section respectively. Each yoke plate is supplemented with two arrays of magnets which are magnetized as shown in Fig.1.



(a) (b)

Fig.1. Configuration of proposed three-phase TFPMLM. (a) Cross sectional view and (b) View configuration along the moving direction.

Each armature unit is spatially separated by 120° in electrical degree with the field poles and all the armature coils are arranged into three-phase symmetrical windings. By supplying three-phase symmetrical ac current to armature coils, the proposed motor can operate as a normal three-phase synchronous linear motor.

III. Magnetic Field Analysis by SC Mapping

SC mapping is a conformal mapping that transforms a domain with a complex structure to anther domain with a simple structure. The analytical solution is easier to obtain in the domain with a simple structure, after that mapping the solution back to the original domain. However, the novel TFPMLM has a 3-D magnetic circuit structure which makes hard to analyze the motor using the SC mapping method directly. Therefore the 2-D analysis model of the motor must first be built by simplifying equivalently 3-D magnetic circuit structure of the novel TFPMLM.

A. The SC Analytical Model of the TFPMLM

To simplify the analysis, such assumptions are made as follows: 1) the permeability of the ferromagnetic material is infinite; 2) the Magnet has linear demagnetization characteristics.

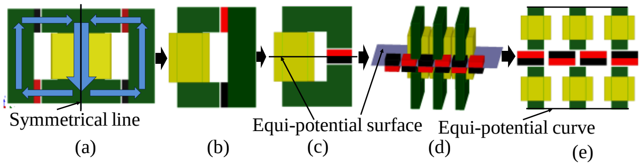


Fig.2. The equivalent transformation of TFPMLM.

The procedure of simplifying 3-D structure of the TFPMLM into a 2-D model is shown in Fig. 2. The motor has a symmetrical structure both in mechanism and electromagnetism as shown in Fig. 2(a), therefore it can be simplified into a C-shape linear motor as shown in Fig. 2(b), and then into the configuration as in Fig. 2(c) or in Fig 2(d), the real 3-D expression. There is an equi-potential surface in the symmetrical plane of the C-shape linear as shown in Fig.2(c) and (d), whose potential value is identical to that of infinity. As a result, the TEPMLM turns into 2-D magnetic model as shown in Fig.2 (e). At last, the equivalent model of the TFPMLM that SC mapping which can be adopted to solve its magnetic field and calculate its back voltage and force waveforms is obtained as shown in Fig. 3.

B. Analysis with SC Mapping Method

When analyzing magnetic field with SC mapping method, the complicated polygon which represents the equivalent 2-D mode of TFPMLM in the ω-plane shown in Fig.3 first should be mapped into a rectangle, a very simplified figure located in the z-plane by SC inverse transformation. Then the magnetic field in the z-plane is resolved easily, and the magnetic field in ω-plane, meaning that in the real TFPMLM can be reached by SC transformation. The SC transformation and its inverse one are shown in Fig.4. The magnetic vector potential produced by the line current I_i in rectangle of z-plane is expressed as [2]

$$A_{i-z} = -\frac{\mu_0 I_i}{4\pi}\left[\ln(\cosh\frac{\pi(x-x_i)}{\Delta y} - \cos\frac{\pi(y+y_i)}{\Delta y}) + \ln(\cosh\frac{\pi(x-x_i)}{\Delta y} - \cos\frac{\pi(y-y_i)}{\Delta y})\right] \tag{1}$$

where Δy is the height of the rectangle, (x_i, y_i) is the coordinate of I_i in the z plane, μ_0 is the free space permeability. The flux density produced by I_i in the ω-plane is given by

$$B_{i\text{-u}} + jB_{i\text{-v}} = \left(\frac{B_{i\text{-x}} + j(B_{i\text{-y}} + \frac{\Delta A_{i\text{-z}}}{\Delta x})}{\overline{f'(z)}}\right) \tag{2}$$

From the equation (2), the back voltage and force waveforms can be obtained accordingly.

IV. 3-D FEM And Experiment Verification

The air-gap flux density distribution and back voltage and force ripple waveforms when the prototyped TFPMLM is at no load, and the force waveform when it runs at i_d=0, i_q=4A, are obtained through SC mapping method and 3-D FEM respectively, as shown in Fig. 4. It can be seen from Fig.4 that the results from SC mapping method much coincide with that from 3-D FEM.

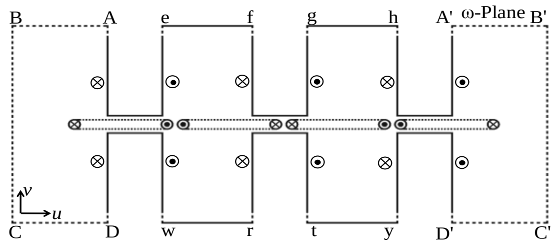


Fig.3. The equivalent SC analysis model of the TFPMLM

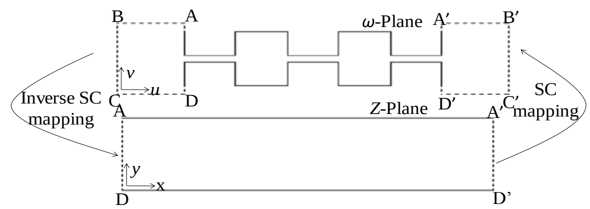


Fig.4. Illustration of SC mapping between different domains in SC method

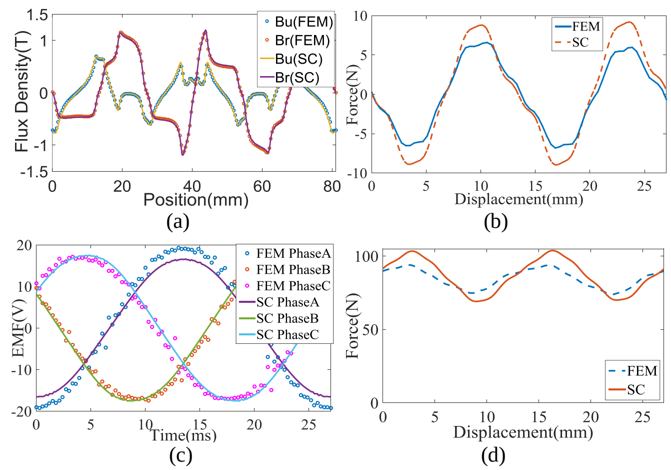


Fig.5. Results calculated by SC method and 3-D FEM. (a), (b) and (c) are air-gap flux density distribution, cogging force and EMF waveforms when at no-load and (d) is thrust force waveform when at load.

V. Conclusion

In this paper, Double-sided double-excited transverse-flux permanent magnet linear Motor is presented, which supplements the advantages from transverse-flux configuration and with simple structure and without unilateral magnetic force. The SC method is used to calculate its air-gap flux density distribution and then its voltage and force waveforms, the results of which are verified by that from 3-D FEM.

Acknowledgment

The authors would like to thank the Department of Science and Technology of Shandong Province (2015ZDXX0601b01)

References

[1] T. C. O'Connell, P. T. Krein, "A Schwarz–Christoffel-based analytical method for electric machine field analysis," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 565–577, Sep. 2009.

[2] L. Zeng, X. Chen, X, Li; "A Thrust Force Analysis Method for Permanent Magnet LinearMotor Using Schwarz–Christoffel Mapping and Considering Slotting Effect, End Effect, and Magnet Shape". *IEEE Trans. Magn*, Vol. 51, no. 9. 8107609, 2015.