Finite Element Modeling of Electromagnetic Force for Magnetic Levitation Planar Motor

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Abstract:
In this paper, the finite element model of the magnetic levitation planar motor is established based on the finite element simulation software COMSOL, and the three directional forces of the electrified coil group are obtained. To verify the correctness of the established finite element model, the coil group is equivalently replaced, and the Lorentz force formula is used to establish the analytical model of the forces in all directions of the coil. The difference between the analytical model and the finite element model is judged by calculating the root mean square error of the analytical model and the finite element model. The obtained results prove that the difference between the analytical model and the finite element model is small, which proves the correctness of the finite element model established in this paper.

Keywords: *Finite element; Coil array; Lorentz Force Volume Integral; Surface motor*

1 INTRODUCTION

Since the beginning of the 21st century, human beings have entered the fast lane of the information age. The modern information industry has gradually become the mainstream of the country and society. All walks of life are closely related to the modern information industry. Informatization is changing human life at a very fast speed, and the integrated circuit is the hardware support of the modern information industry. Its manufacturing level and the degree of industrial development have a profound impact on the country’ s economy, national defense and international status. As a large-scale integrated circuit, namely the processing and manufacturing equipment of the chip, the lithography machine can also show the high-end manufacturing level of the whole country to a certain extent. The new generation of lithography machine is mainly based on the magnetic suspension plane motor as the main structure. Compared with the traditional air-floating lithography machine, the new generation of lithography machine with the magnetic suspension plane motor as the main body has high acceleration, high precision, six degrees of freedom and simple structure. Therefore, the research on the magnetic suspension plane motor has a great role in promoting the national chip strategic plan.

The common magnetic levitation plane motors are divided into two types, namely, the moving coil magnetic levitation plane motor and the moving magnet steel magnetic levitation plane motor. However, they are all composed of Halbach permanent magnet array and coil array. The Halbach permanent magnet array provides the magnetic field, and the electrified coil moves under the action of electromagnetic force in the magnetic field. The Halbach permanent magnet array was first proposed in 1980 and was first applied to the electronic oscillator. Its main structure is composed of a large permanent magnet and four small permanent magnets, as shown in Fig. 1 [10] [11]. Through a specific arrangement distribution, the permanent magnet array has the characteristics of one side of the magnetic field significantly enhanced and the other side reduced. The magnetic field formed by this characteristic has the excellent characteristics of sinusoidal distribution and less harmonic content. The Halbach permanent magnet array is used as the magnetic field provider in the mainstream magnetic levitation planar motor [3].

In this paper, the moving coil magnetic levitation planar motor is taken as the research object. The finite element models of Halbach permanent magnet array and coil array are established by the finite element software COMSOL, and the force in each direction of X, Y and Z of the coil array is measured. The analytical model of the coil force is established by using the Lorentz force formula, and the finite element model is verified.

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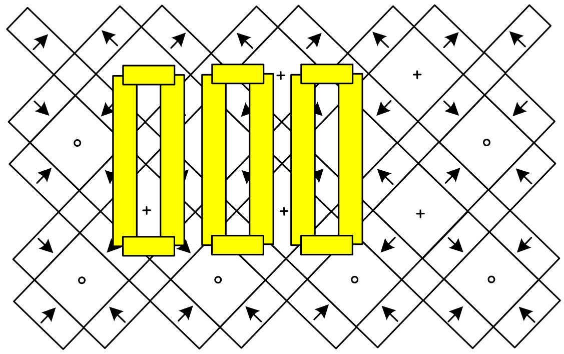


Figure 1: Halbach permanent magnet array and coil group.

2 ANALYTICAL MODELING

There are mainly three methods to establish the analytical model of the electromagnetic force of the coil, namely, the Lorentz force formula method, the virtual work method and the Maxwell stress tensor method. Since the magnetic levitation planar motor has no iron core interference, it is only necessary to consider the influence of the-magnetic field generated by the permanent magnet array on the coil. Therefore, the Lorentz force formula is suitable for establishing the analytical model of the coil force of the magnetic levitation planar motor. The force of the coil can be obtained by integrating the volume of each part of the coil. However, due to the existence of four chamfers of the coil, it is difficult to establish a specific model of the force of this part in the chamfer part [5]. Therefore, the equivalent coil model is used to establish the analytical model. The schematic diagram is shown in Fig. 2.

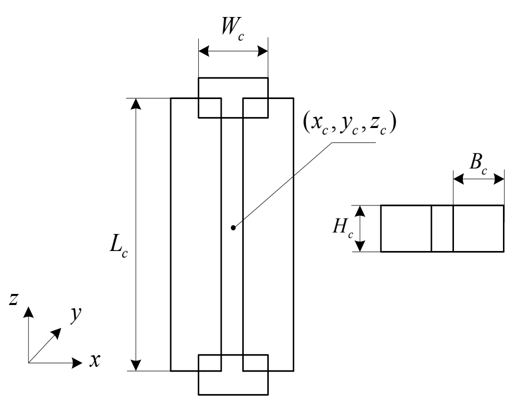


Figure 2: Diagram of equivalent coil model.

Assuming that the shape of the coil is regular, the current distribution is uniform, and the current in the counter clockwise direction is defined as a positive direction. According to the Lorentz force formula method, the mathematical analysis model of the coil force can be established [4] [9]. The formula is as follows (1)

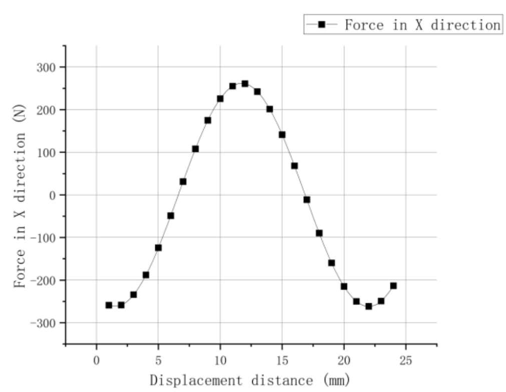
$$\int_V \boldsymbol{J} \times \boldsymbol{B}\, dV \tag{1}$$

According to the coil diagram in Fig. 2, the coil and the permanent magnet array are made to be 45° angle, and the coordinate system with the centroid of the coil (x_c , y_c , z_c) as the origin is established. Assuming the current density of the coil is $\boldsymbol{J}_c$, $\boldsymbol{B}$ is the static magnetic flux density vector, and the force of each coil can be calculated according to the formula (1) [6]. Taking a long side of any coil as an example, the thrust in X direction and Z direction on this side are:

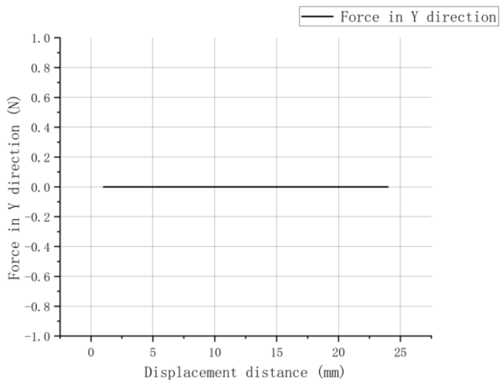
$$Fx = \int_{z_c-\frac{h_c}{2}}^{z_c+\frac{h_c}{2}} \int_{y_c-\frac{l_c}{2}}^{y_c+\frac{l_c}{2}} \int_{x_c+\frac{w_c}{2}-\frac{b_c}{2}}^{x_c+\frac{w_c}{2}+\frac{b_c}{2}} -\boldsymbol{J}_c \times \boldsymbol{B}\, dxdydz \tag{2}$$

$$Fz = \int_{z_c-\frac{h_c}{2}}^{z_c+\frac{h_c}{2}} \int_{y_c-\frac{l_c}{2}}^{y_c+\frac{l_c}{2}} \int_{x_c+\frac{w_c}{2}-\frac{b_c}{2}}^{x_c+\frac{w_c}{2}+\frac{b_c}{2}} \boldsymbol{J}_c \times \boldsymbol{B}\, dxdydz \tag{3}$$

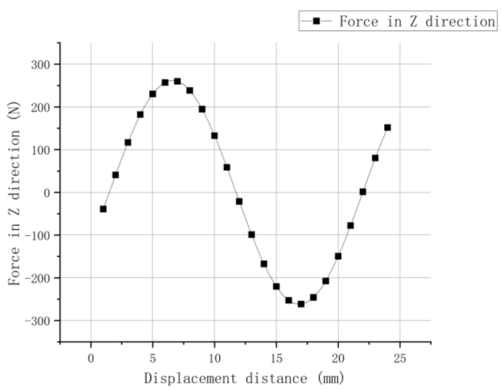
The measurement of each part of the coil can be completed only by modifying the upper and lower limits of Y and X integrals and current density direction $\boldsymbol{J}_c$ of current density on each side of other coils according to the specific size of the coil. For the measurement of the two outer coils of the coil group, it is necessary to find the specific coordinates of the various centroids respectively. After the calculation of the formula (2) and (3), the resultant force of the XYZ direction of the coil group can be obtained by superposition of the values. The specific results are shown in Fig. 3.



(a) Analytical model X direction force size



(b) Analytical model Y direction force size



(c) Analytical model Y direction force size

Figure 3: Directional Receiving Diagrams of Coil Groups.

3 FINITE ELEMENT MODELING

Finite element analysis is a kind of simulation of real geometry or system based on mathematical approximation analysis. The simulation object is divided into a number of unit elements that affect each other by meshing, so that the simulation is as close as possible to the reality [8]. The common finite element simulation software is Ansys and COMSOL. In this paper, COMSOL is used as the finite element simulation software for finite element modelling.

Through the finite element simulation software COMSOL, the Halbach permanent magnet array is first modelled. Its main structural situation is shown in Fig. 1 above, and its main parameters are shown in Table 1 below.

Table 1: Halbach permanent magnet array parameters

Parameters	Symbol	Unit	Value
Residual flux density of permanent magnet	M_0	Tesla	1.41
Pole distance of permanent magnet array	τ	mm	15
Electrode distance	τ_n	mm	10.6
Large permanent magnet length	B_{m1}	mm	10
Length of small permanent magnet	B_{m2}	mm	5
Permanent magnet thickness	H_m	mm	10

According to the appeal table, the finite element model of a Halbach permanent magnet array is established by COMSOL finite element simulation software. the material is N50M, namely NdFeB material. The magnetic property of this material is a permanent magnet only next to the absolute zero-degree holmium magnet, which is an excellent permanent magnet material. The magnetization is carried out according to the magnetization direction of the large and small permanent magnets shown in Fig. 1, so that the residual flux density of the large and small permanent magnets is 1.41 Tesla, and the recovery permeability is set to 1.05 [2] [7]. After the magnetization is completed, the large and small permanent magnets are arranged and combined according to Fig. 1. So far, the finite element model of Halbach permanent magnet array is established to the end.

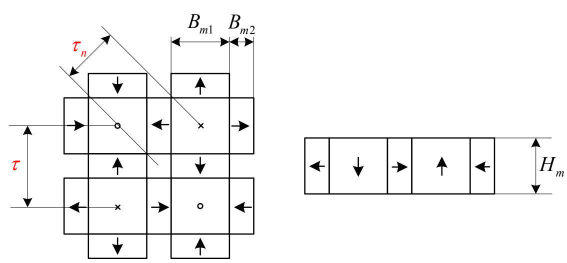


Figure 4: Halbach Unit Module Diagram.

For the magnetic levitation planar motor, its coil array is constantly moving under force, and its force and torque are derived from the interaction between the current-carrying coil and the magnetic field of the permanent magnet, namely the Lorentz force. Therefore, the finite element model of the coil is established to analyze the change direction and size of the Lorentz force of the coil.

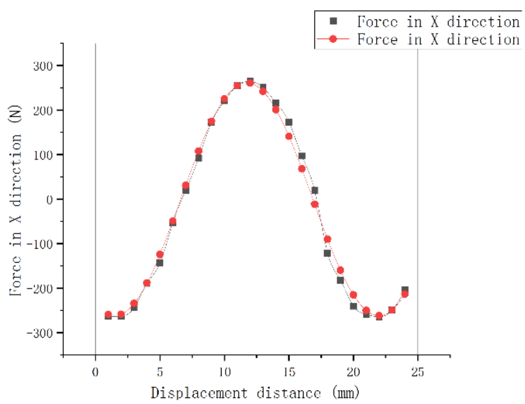
Table 2: Parameters of electromagnetically levitated planar motor coil

Parameters	Symbol	Unit	Value
Coil turn width	B_c	mm	4
Coil length	L_c	mm	42.4
Coil width	W_c	mm	6.4

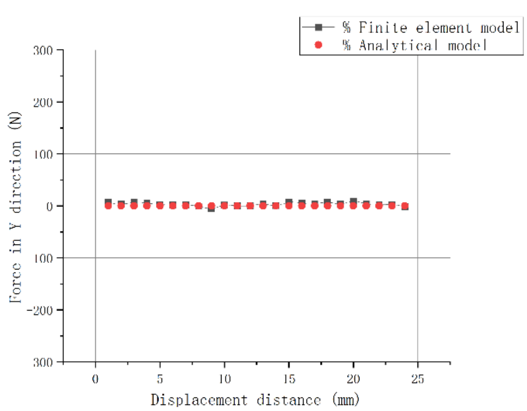
Coil thickness	H_c	mm	4
Number of coils	N		165

Now the finite element model of the coil group is established. The parameters of the coil are shown in Table 2. According to Table 2 and Figure 4, three identical coils are established to form the coil group. The force of the X, Y and Z components of the coil group is modelled and analysed.

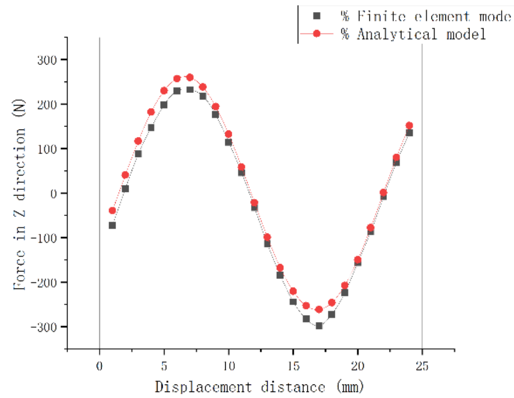
Through the finite element simulation software COMSOL, the author establishes the finite model of the Halbach permanent magnet array and the magnetic levitation plane motor of the electric coil. By moving the coil group, the magnetic force and the transformation trend of the X, Y and Z components of the coil group are measured. The measured results are as follows: Figure 4. From the finite element results, it can be concluded that the electromagnetic components in the X and Z directions are distributed by quasi-sinusoidal function, and the Y direction is centered on the X axis. The value of the Y direction is much smaller than that of the X and Z directions, which is in line with the expected analysis results.



(a) X direction force of finite element model.



(b) Y direction force of finite element model.



(c) Z direction force of finite element model.

Figure 5: Simulation results of finite element model.

So far, the establishment of the analytical model of the coil group is over.

In this paper, the finite element model of a magnetic levitation planar motor is established by COMSOL finite element simulation software, and the forces in three directions of X, Y and Z of the coil composed of three coils are obtained. In order to verify the correctness of the finite element model, the electrified coil with chamfer is approximately equivalent to the electrified coil composed of four cuboids, and then the analytical model of the simple equivalent electrified coil group is established by Lorentz force formula method. In order to compare the difference between the finite element model and the analytical model, and the data of the finite element model and the analytical model show a sine law. Therefore, the root mean square error in the measurement range is used to measure the difference between the two data.

$$E_{rms} = \sqrt{[\sum_{i=1}^{n}(V_{mi} - V_{ti})^2]/n} \tag{4}$$

E_{rms} in the equation is expressed as root mean square error, V_{mi} is the value of the analytical model, V_{ti} is the value of the finite element model, and i is the number of measured data. Through the formula (4), the mean square error values of X, Y and Z directions are obtained, the value of X direction is 16.29, the value of Y direction is 4.33, and the value of Z direction is 23.06 [1]. Because the coil in the analytical model is an equivalent model, and the full-size coil model is not used, there must be some differences between the analytical model and the finite element model. According to the size of the root mean square error calculated, it can be seen from the number that the difference between the analytical model and the finite element model is within the error range. Therefore, the finite element model of the magnetic levitation planar motor established by COMSOL finite element simulation software in this paper is correct.

4 CONCLUSIONS

In this paper, the finite element analysis software COMSOL is used to model the Halbach permanent magnet array and the coil group of the magnetic levitation planar motor, and the electromagnetic force in each direction of the coil group is simulated and calculated, and the electromagnetic force of the finite element model is obtained. In order to verify the correctness of the model, the analytical model of the coil group is established by Lorentz force formula method. The electromagnetic force of the coil group is calculated by the analytical model, and the difference between the analytical model and the finite element model is verified by calculating the root mean square error of the three directions of XYZ. The results show that the difference between the two models is small, which lays a foundation for establishing a more accurate magnetic levitation planar motor model.

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