Research on Coupling Property of Vertical and Transverse Force of Maglev Platform

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***Abstract*—Maglev platform is a support platform which has special advantages, such as no contact， no lubrication, easy maintenance, long service life and high precision. It has a very broad application prospects. In the research of maglev platform, the design and optimization of electromagnets is critical. In this paper, the overall structure of the maglev platform and electromagnets has been introduced firstly. According to the technical requirements with large span and big air gap, the parameters of iron cores and coils are given for the following calculation and simulation. Secondly, in order to study the property of vertical and transverse force produced by the electromagnets of maglev platform, the calculation based on magnetic circuit method of the bearing force of toroidal and U-type electromagnets are carried out. Mathematical analytical model of vertical and transverse magnetic force was deduced by using virtual displacement method. The vertical and transverse magnetic force dependence on vertical gap and transverse displacement was analyzed. Coupling between vertical and transverse magnetic force was studied. The forces was simulated by finite-element method and the simulation results were compared with the calculated results. Theoretical results for designing vertical and transverse decoupling control system were provided. Lastly, the bearing capacity, magnetic field distribution and magnetic induction intensity of the simulation model, which is established based on previous parameters, are analyzed through Ansoft finite element method. Combining with smoothing and trimming, defects of the electromagnets are improved. The result of analysis on the characteristics of the electromagnets is helpful to improve the control precision and stability of the platform, and the study of the issue involved has very high theory value and realistic significance.**

I. INTRODUCTIONS

Due to its non-contact nature, the maglev platform are able to provide the accurate suspension without considering the deformation caused by a large change in temperature. Tremendous structure of maglev platform in various fields have been presented by researchers, and many of them are applied in the field of precision manufacturing. Scholars from NUAA put forward a maglev vibration isolation platform, which suppressed the vibration of the supporting foundation for the platform by electromagnetic force [1]. In the current IC maglev manufacturing field, some domestic and international researches about structures, decoupling methods and control methods were summarized in the paper [2], which introduced the Y-type, Δ-type, TU-type and sandwiched structures. The significant characteristics of the maglev platform applied in this field are small stroke, small load and high positioning accuracy. Linear motion platform is another area where magnetic suspension technology is widely used. Researchers from CAS described a new maglev model vehicle using hybrid magnets for levitation with linear generator [3]. A novel magnetic levitation feeding platform based on the hybrid excited linear synchronous motor are proposed, in which the driving system and levitation system share a common airgap magnetic field [4]. Shandong University's scholars have developed a linear motion platform that uses three pairs of U-type electromagnets to achieve levitation and self-recovery guidance [5]. The paper [6] gave a model of a maglev mobile platform used in large CNC machine tools. The platform is 10 meters in length, 1.8 meters in width and 500 kilograms in weight. It realizes one-dimensional linear motion of the platform.

In the working process of the magnetic levitation platform, the platform will deviate from the reference position due to external disturbances. The movement of the floating position will change the air gap that cause the change of the electromagnetic force. The more complicated problem is that the vertical change of air gap force will change the transverse force and further cause the change of the transverse displacement. It is necessary to study the coupling characteristics between vertical and transverse force. Research on the coupling of forces in different directions has received more attention. Published papers [7, 8, 9] deal with changes in the bearing capacity of electromagnets, analysis of transverse bearing capacity and edge effect of hybrid magnetic bearings, using magnetic circuit analysis and virtual displacement methods. These studies are all aimed at the rotating magnetic system. There are few research papers about the coupling of the magnetic levitation platform.

The research object of this paper is a kind of maglev platform with large span, large air gap and large bearing capacity. The virtual displacement method is used to establish the analytical model for the bearing capacity of the electromagnet. The finite element analysis software is used to simulate and analyze the bearing capacity of the electromagnet. The results show that the vertical and transverse bearing capacity exist a certain relationship with the vertical and transverse displacement. It is designed to explore the coupling characteristics of the vertical levitation force and the transverse levitation force.

II. STRUCTURE OF THE PLATFORM AND ELECTROMAGNETS

The square suspension platform on this article has a length of 1.8m and a weight of 600kg. The levitation in the vertical direction of the platform is achieved by four sets of toroidal electromagnets symmetrically distributed on the four corners of the square, and the positioning unit electromagnet is U-shaped.

The toroidal iron core is shown in Figure 1. The toroidal core has advantages of good sealing for magnetic circuit and less magnetic leakage. Comparing the rectangular magnetic poles with the same cross-sectional area, the cylindrical inner magnetic pole can reduce the circumference of each coil, which is conducive to reducing the copper loss.

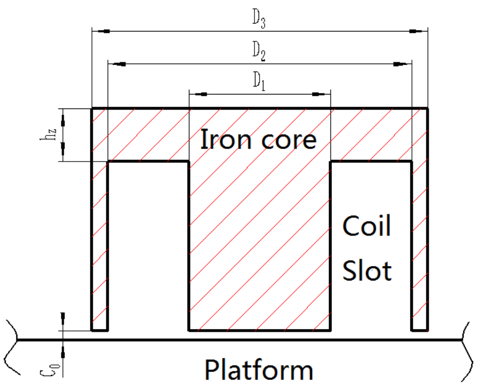

Figure 1. Profile of toroidal iron core

The electromagnet model of the positioning unit is shown in FIG. 2, and a widely used U-type structure is adopted. The design parameters of the U-type core are obtained by a magnetic circuit estimation method.

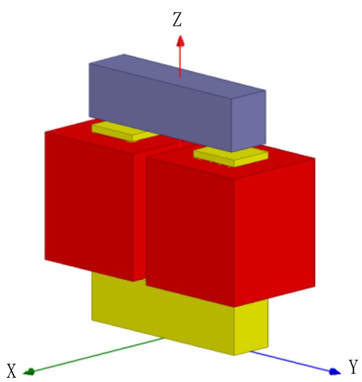

Figure 2. Structure of U-type iron core

III. COUPLING ANALYSIS OF VERTICAL AND TRANSVERSE BEARING CAPACITY

The first thing to note is that in order to unify the terms of magnetic bearings and maglev platforms, the vertical direction of the toroidal magnet is called axial in calculation and simulation, and the transverse direction is called radial.

According to the electromagnetic field theory, the axial bearing capacity and radial bearing capacity at the air gap can be obtained by the virtual displacement method.

The axial bearing capacity of toroidal magnetic pole is:

$$\begin{aligned} F_z &= \frac{\partial W}{\partial z} \approx -\frac{1}{2}F_{mi}^2\frac{\partial G_i}{\partial z} - \frac{1}{2}F_{mo}^2\frac{\partial G_o}{\partial z} \\ &= \frac{F_{mi}^2\mu_0 R_1}{2}\left[\frac{\pi R_1 - 4r}{z^2} + \frac{16r}{(r+2z)^2}\right] + \\ &\quad \frac{F_{mo}^2\mu_0(R_3+R_2)}{2}\left[\frac{\pi(R_3-R_2)-4r}{z^2} + \\ &\quad \frac{16r}{(r+2z)^2}\right] \end{aligned} \tag{1}$$

The radial bearing capacity is:

$$\begin{aligned} F_r &= \frac{\partial W}{\partial r} \approx -\frac{1}{2}F_{mi}^2\frac{\partial G_i}{\partial r} - \frac{1}{2}F_{mo}^2\frac{\partial G_o}{\partial r} \\ &= -\left[\frac{F_{mi}^2\mu_0 R_1}{2} + \frac{F_{mo}^2\mu_0(R_3+R_2)}{2}\right] \cdot \\ &\quad \left[\frac{4}{z} - \frac{16z}{(r+2z)^2}\right] \end{aligned} \tag{2}$$

Where G_i and G_o are the magnetic conductances of the inner and outer air gaps of the pole, R_1 is the inner magnetic pole radius, R_2 is the inside diameter of outer magnetic pole, and R_3 is the outside diameter of outer magnetic pole. The variation of the axial force with axial displacement and radial displacement can be analyzed by defining the axial bearing force factor, A_z which is based on Formula (1),

$$A_z = \frac{\pi t - 4r}{z^2} + \frac{16r}{(r+2z)^2} \tag{3}$$

where t is the thickness of the magnetic pole. Similarly, the radial force factor A_r is used to analyze the variation of the radial force with radial displacement and axial displacement,

$$A_r = \frac{4}{z} - \frac{16z}{(r+2z)^2} \tag{4}$$

The Radial / axial force coefficient X of the toroidal magnetic pole is defined by Formula (5).

$$X = \left|\frac{A_r}{A_z}\right| = \left[\frac{4}{z} - \frac{16z}{(r+2z)^2}\right] \Big/ \left[\frac{\pi t - 4r}{z^2} + \frac{16r}{(r+2z)^2}\right] \tag{5}$$

The change characteristics of axial displacement, radial displacement and radial/axial load capacity coefficient X are shown in Fig. 3. According to the graph, when the radial displacement r increases, the coefficient X increases and the slope becomes larger. As the axial displacement z increases, X becomes smaller and the slope is smaller.

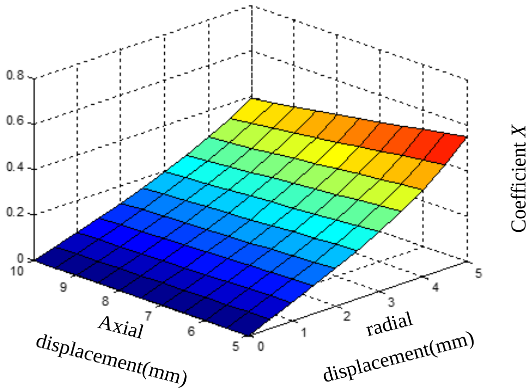

Figure 3. Relationship between radial and axial force coefficient X of toroidal magnet with axial air gap and radial displacement.

The vertical and transverse forces of U-shaped electromagnets can also be obtained by the virtual displacement method. Vertical bearing capacity is,

$$F_g = \frac{\partial W}{\partial g} \approx -\frac{1}{2}F_{ml}^2\frac{\partial G_u}{\partial g} - \frac{1}{2}F_{mr}^2\frac{\partial G_d}{\partial g} = \frac{F_{ml}^2\mu_0 b}{2}[\frac{a-e}{g^2}+\frac{0.27e}{(e+0.52g)^2}]+\frac{F_{mr}^2\mu_0 ba}{2g^2} \tag{6}$$

Transverse bearing capacity is,

$$F_e = \frac{\partial W}{\partial e} \approx -\frac{1}{2}F_{ml}^2\frac{\partial G_u}{\partial e} - \frac{1}{2}F_{mr}^2\frac{\partial G_d}{\partial e} = \frac{F_{ml}^2\mu_0 b}{2}[\frac{1}{g}-\frac{0.27g}{(e+0.52g)^2}] \tag{7}$$

where a and b are the side lengths of the magnetic poles. Assume that the magnetic pressure drop at the two air gaps is the same, which is half of the total magnetic pressure drop, ie

$$F_{ml}=F_{mr}=F_m/2 \tag{8}$$

Where F_m is the total magnetomotive force. Substituting formula (8) into formula (6) and formula (7), following equations can be obtained,

$$F_g = \frac{F_{ma}^2\mu_0 b}{8}[\frac{a-e}{g^2}+\frac{0.27e}{(e+0.52g)^2}+\frac{a}{g^2}] \tag{9}$$

$$F_e = \frac{F_{ma}^2\mu_0 b}{8}[\frac{1}{g}-\frac{0.27g}{(e+0.52g)^2}] \tag{10}$$

The transverse / vertical force coefficient T of the U-type magnetic pole is defined by Formula (11).

$$T = \left|\frac{F_e}{F_g}\right| = \frac{[\frac{1}{g}-\frac{0.27g}{(e+0.52g)^2}]}{[\frac{a-e}{g^2}+\frac{0.27e}{(e+0.52g)^2}+\frac{a}{g^2}]} \tag{11}$$

The variation characteristics of U-shaped magnetic pole vertical displacement and transverse displacement and transverse/ vertical bearing force coefficient T are shown in Fig. 4. From the figure, it can be seen that T increases with the increase of the transverse displacement e, and the change tendency becomes smaller, and finally it tends to be saturated. At the same time, when the transverse displacement is large, T increases as the vertical displacement g increases.

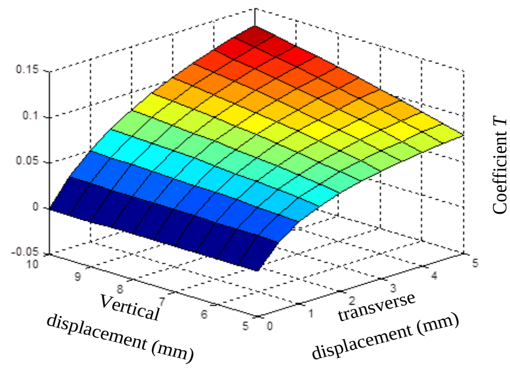

Figure 4. Relationship between the transverse and vertical force coefficient T of U-type magnet with the vertical and transverse displacement.

IV. SIMULATION OF ELECTROMAGNETIC FIELD

A 3D simulation model of a toroidal electromagnet is constructed using ANSYS software, and is composed of an iron core, an excitation coil, and a rotor. Fig. 5 shows a 3D simulation model of the toroidal electromagnet.

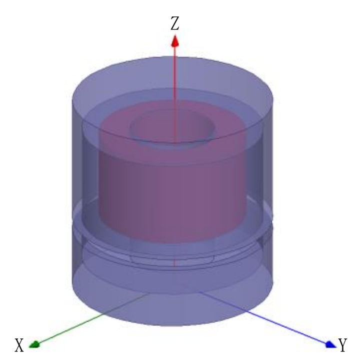

Figure 5. 3D Simulation Model of toroidal electromagnet.

Figure 6 shows the magnetic induction scalar map of a toroidal electromagnet. It can be seen from the figure that the distribution of magnetic induction intensity is axisymmetric. However, the magnetic induction is higher at the edges and at the corners of the magnetic poles, and is particularly magnetically saturated at the edges and at the corners of the inner magnetic poles. Because the toroidal electromagnet seal is relatively closed, the heat dissipation is poor, which lead high local temperature. In order to prevent the phenomenon of local magnetic saturation, the edge and corner of the poles are smoothed appropriately, as shown in Figure 7. After the magnetic poles are smoothed, the local magnetic saturation phenomenon is well improved, which is very favorable for improving the reliability and stability of the system.

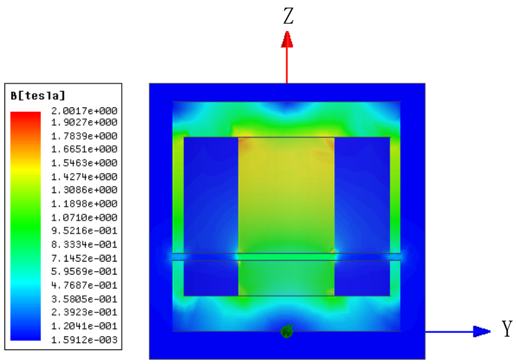

Figure 6. Induction scalar map of toroidal electromagnet

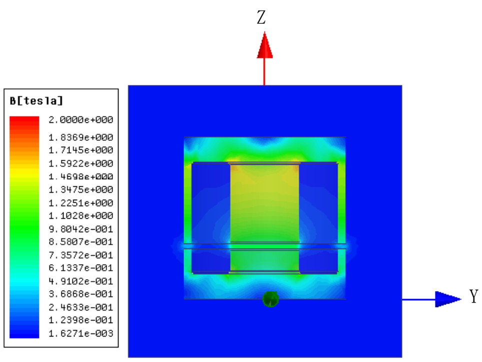

Figure 7. Induction scalar map of toroidal electromagnet after smoothing.

Figure 8 shows the magnetic induction at the air gap for different air gap lengths of the ring-type electromagnets. It can be seen that as the axial air gap increases, the air gap magnetic induction decreases. In addition, as the axial air gap of the curve increases, the length of the distance corresponding to the peak of the curve decreases, which indicates that the radial component of the magnetic flux at the air gap increases as the air gap increases.

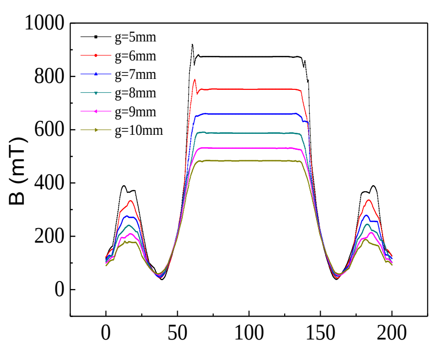

Figure 8. Magnetic induction at the air gap of toroidal electromagnets with different air gap lengths.

Similarly, most areas of the U-type electromagnet core do not reach the magnetic induction saturation region, but are high at the four corners of the magnetic pole surface. In order to avoid saturation of the local magnetic induction intensity when processing the magnetic pole, the four corners of the magnetic pole surface are smoothed.

Figure 9 is a graph of the magnetic induction at the air gap for U-type electromagnets with different axial air gap lengths. It can be seen that as the axial air gap increases, the air gap magnetic induction decreases. Similarly, the length of the curve corresponding to the peak length decreases, the greater the axial air gap, the greater the magnetic leakage.

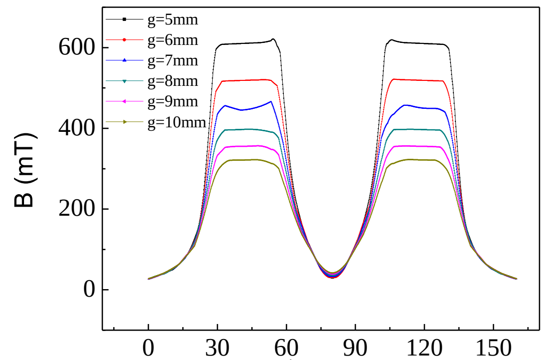

Figure 9. Magnetic induction at the air gap of U-type electromagnet with different axial air gap length

V. CONCLUSION

For the two structures of magnetic pole of toroidal electromagnet and the magnetic pole of U-type electromagnet, the analytical expressions of vertical and transverse force are derived by virtual displacement method.

For the relationship between vertical displacement and transverse displacement and vertical bearing capacity and transverse bearing capacity, the annular magnetic pole and the U-shaped magnetic pole exhibit an approximate characteristic: the vertical force decreases rapidly with the increase of the vertical displacement, and decreases with the increase of transverse displacement as approximately linear. The transverse force decreases with the increase of the vertical displacement. When the transverse displacement increases, the transverse force increases first and then tends to be saturated.

When analyzing the coupling characteristics of vertical force and transverse force, the toroidal magnet and U-shaped magnet show different characteristics: when the transverse displacement increases, the transverse/vertical force coefficient of toroidal electromagnets increases, and the slope becomes larger; the same coefficient of U-type electromagnets increases, but the slope becomes smaller. This shows that the transverse force of the toroidal magnet tends to increase with transverse displacement, and that of the U-type magnet tends to saturate faster. When the vertical displacement increases, the transverse/vertical force coefficient of the toroidal magnet decreases but the change is not obvious, and the transverse/vertical force coefficient of the U-shaped magnet increases with the increase of the vertical air gap. This shows that when the vertical gap of the U-shaped magnet increases, the vertical force decreases faster than the transverse force, and the forces of toroidal magnet decreases approximately in the same proportion.

The research results in this paper provide a theoretical basis for the decoupling control of vertical and transverse magnetic levitation system. Using simulation software to simulate the vertical force and transverse force, the vertical force calculation and the simulation results are in good agreement, and the transverse force difference is relatively large, which means that it is necessary to consider the magnetic pole thickness, air gap magnetic flux edge effect and magnetic flux leakage when calculating the transverse force.

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