

Analysis of 3D Magnetic Field of Magnetic Suspension Spherical Reluctance Motor

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Abstract—It is a very complicated problem that analyzing and calculating the magnetic field of the magnetic suspension spherical reluctance motor, because the structure of the stator and rotor, the distribution of magnetic field present three-dimension. By calculating 3-D magnetic field and analyzing the magnetic field of the magnetic suspension spherical reluctance motor, Then we draw the magnetic flux density distribution curve of the salient pole stator and rotor in different position, when the motor stator is in different current.

Keywords—magnetic suspension; finite element method; 3D magnetic field; spherical reluctance motor

I INTRODUCTION

Multiple degrees of freedom motor refers to a kind of motor which has two or three rotating degrees, the motor can rotate round fixed-point axis of the space. The spherical motor belongs to multiple degrees of freedom (MDOF) motor. MDOF motor has a wide application prospect in robots, multiple coordinates mechanical processing center, aerospacecraft, electric gyroscope, all-round tracking antenna, turret turntable, prosthetic human body, medical equipment, camera work station, panorama photography work station, blender, globe valve, and other multiple degrees of freedom equipments.^[1] It is too difficult to simplify magnetic field of spherical motor by using 2D magnetic field because it has complex boundary conditions, anisotropy, nonlinearity and other characteristics, and that it is a typical 3D magnetic field, we must further discuss its calculation problem. Currently, the subject about the design and analysis of spherical motor is still being studied at home and abroad.^[2-3] This study plans to use 3D finite element analysis (FEA) method to calculate and analyze the magnetic field of MDOF magnetic suspension spherical reluctance motor in order to offer some basis for the design and calculation of MDOF magnetic suspension spherical reluctance motor.

II. THE BASIC STRUCTURE OF MAGNETIC SUSPENSION SPHERICAL RELUCTANCE MOTOR

The stator and rotor 3D structure of magnetic suspension spherical reluctance motor are shown in Fig.1, the rotor is a unit salient pole sphere that has grooves, and it locates in the middle of the motor; Four stators are symmetrically distributed on the

equator line of spherical rotor. stator 1 and stator 3 keep coaxial with the x-axis; the function is to drive the rotor to rotate around x-axis and produce magnetic suspension force that makes the rotor stabilize in the x-axis direction, Stator 2 and stator 4 keep coaxial with the y-axis, which is aimed at driving the rotor to rotate around the y-axis and producing magnetic suspension force that makes the rotor stabilize in the y-axis direction; Stator 5 is located in the top of spherical rotor and keeps coaxial with z-axis, its function is to drive the spherical rotor to rotate around z-axis and produce stable magnetic suspension force in the z-axis direction.

The surface of spherical rotor of magnetic suspension spherical motor has mutual orthogonal grooves. The stator includes six salient poles and one ladder circle. Based on reluctance motor principle, there are multiphase windings which drive the stator to rotate in salient poles of stator. After each phase winding is charged with electricity, it not only produces electromagnetic torque which drives the rotor to rotate, but also provides radial magnetic suspension force for rotor.^[4]

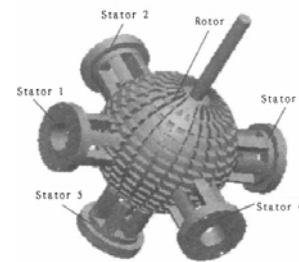


Fig.1 The structure of the magnetic suspension spherical reluctance motor

III. ANALYSIS OF MAGNETIC FIELD OF MAGNETIC SUSPENSION SPHERICAL RELUCTANCE MOTOR

A. The Basic Principle of 3D Magnetic Field Calculation of Magnetic Suspension Spherical Reluctance Motor

In the finite element of 3D magnetic field, three components of the magnetic vector potential A are A_x , A_y , A_z .^[5-6] In the magnetic field of 3D linear media, the magnetic vector potential A satisfy following demands under $\nabla \cdot A = 0$:

$$\nabla^2 A = -\mu J, \text{ In the magnetic field } V;$$

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$A|_s = C$, on the boundary S;

Corresponding conditions variational problem is:

$$F(A) = \iiint \left[\frac{1}{2\mu} |\nabla \times A|^2 - J \cdot A \right] dx dy dz = \min, A|_s = C$$

If the whole magnetic field is discrete into k_0 units and p_0 nodes. In the rectangular coordinate system, the magnetic vector potential A_i of any node i has three components, which are called A_{xi}, A_{yi}, A_{zi} ; Therefore, each component of the magnetic vector potential of p_0 nodes can be lined into the following column vector:

$$[A] = [A_{x1} A_{y1} A_{z1} A_{x2} \dots A_{xp}]$$

If each unit has p_0 nodes, the shape function corresponding to node i is P_i^k , and the magnetic vector potential A of any point of each unit can be expressed as $A = \sum_{i=1}^{p_0} P_i^k A_i$. Three components of the magnetic vector potential A are respectively expressed as

$$A_x = \sum_{i=1}^{p_0} P_i^k A_{xi}, A_y = \sum_{i=1}^{p_0} P_i^k A_{yi}, A_z = \sum_{i=1}^{p_0} P_i^k A_{zi}$$

Energy functional $F(A)$ of the whole magnetic field can be expressed as the sum of each unit energy functional:

$$F(A) \approx F(\bar{A}) = \sum_{i=1}^{k_0} F_k(\bar{A})$$

The unit energy functional is

$$F_k(A) = \iiint_k \left[\frac{1}{2\mu} |\nabla \times A|^2 - J \cdot A \right] dx dy dz = \iiint_k \left\{ \frac{1}{2\mu} \left[\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right)^2 + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right)^2 + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right)^2 \right] - (J_x A_x + J_y A_y + J_z A_z) \right\} dx dy dz$$

According to extreme value theory, the variational problem is equivalent to the following equation:

$$\frac{\partial F}{\partial A_{xi}} = \sum_{k=1}^{k_0} \frac{\partial F_k}{\partial A_{xi}} = 0, \quad \frac{\partial F}{\partial A_{yi}} = \sum_{k=1}^{k_0} \frac{\partial F_k}{\partial A_{yi}} = 0, \\ \frac{\partial F}{\partial A_{zi}} = \sum_{k=1}^{k_0} \frac{\partial F_k}{\partial A_{zi}} = 0$$

In the above equation, any unit k after discretization has p_0 nodes. Then the i th node of this unit can be showed as

$$\frac{\partial F_k}{\partial A_{xi}} = \sum_{j=1}^{p_0} \iiint_k \left\{ \frac{1}{\mu} \left[\left(\frac{\partial P_i^k}{\partial y} \frac{\partial P_j^k}{\partial y} + \frac{\partial P_i^k}{\partial z} \frac{\partial P_j^k}{\partial z} \right) A_{xj} - \left(\frac{\partial P_j^k}{\partial x} \frac{\partial P_i^k}{\partial y} \right) A_{yj} - \left(\frac{\partial P_j^k}{\partial x} \frac{\partial P_i^k}{\partial z} \right) A_{zj} \right] - J_x N_i^k \right\} dx dy dz \\ \frac{\partial F_k}{\partial A_{yi}} = \sum_{j=1}^{p_0} \iiint_k \left\{ \frac{1}{\mu} \left[\left(\frac{\partial P_i^k}{\partial x} \frac{\partial P_j^k}{\partial x} + \frac{\partial P_i^k}{\partial z} \frac{\partial P_j^k}{\partial z} \right) A_{yj} - \left(\frac{\partial P_i^k}{\partial x} \frac{\partial P_j^k}{\partial y} \right) A_{xj} - \left(\frac{\partial P_j^k}{\partial y} \frac{\partial P_i^k}{\partial z} \right) A_{zj} \right] - J_y N_i^k \right\} dx dy dz \\ \frac{\partial F_k}{\partial A_{zi}} = \sum_{j=1}^{p_0} \iiint_k \left\{ \frac{1}{\mu} \left[\left(\frac{\partial P_i^k}{\partial x} \frac{\partial P_j^k}{\partial x} + \frac{\partial P_i^k}{\partial z} \frac{\partial P_j^k}{\partial z} \right) A_{zj} - \left(\frac{\partial P_j^k}{\partial x} \frac{\partial P_i^k}{\partial y} \right) A_{yj} - \left(\frac{\partial P_j^k}{\partial y} \frac{\partial P_i^k}{\partial z} \right) A_{xj} \right] - J_z N_i^k \right\} dx dy dz$$

$$\left(\frac{\partial P_i^k}{\partial x} \frac{\partial P_j^k}{\partial z} \right) A_{xj} - \left(\frac{\partial P_j^k}{\partial y} \frac{\partial P_i^k}{\partial z} \right) A_{yj} - J_y N_i^k \} dx dy dz$$

Note that its value is not zero only when i is the node of this unit; Therefore, unit coefficient matrix corresponding to one unit is $[S]_k = [[S_{ij}]_k]$, among the equation is third matrix. $[S]_k$ is composed of $[S_{ij}]_k$ square matrix that the number is $p_0 \times p_0$. The same argument, $[N]_k = [N_{x1}^k N_{y1}^k N_{z1}^k \dots N_{xp_0}^k N_{yp_0}^k N_{zp_0}^k]^T$, among the equation,

$$N_{xi}^k = \iiint_{V_k} J_x P_j^k dx dy dz, \quad N_{yi}^k = \iiint_{V_k} J_y P_j^k dx dy dz, \\ N_{zi}^k = \iiint_{V_k} J_z P_j^k dx dy dz, \quad i = 1, 2, \dots, p_0.$$

We should solve the coefficient matrix of above unit, then realize further expansion, getting the finite element equation that is $[S][A] = [N]$. Solution of above equation is $[A]$.

B. Establishment of Model and the Decision of Boundary Condition

Numerical analysis for electromagnetic field of motor mainly use the finite element method that is the most effective and the most widely used at present, boundary element method, and finite difference method. ANSYS is a kind of finite element analysis software, which is widely used at present.^[7] The basic principle of analysis for electromagnetic field using ANSYS is that processing object first should be divided into finite unit (including some nodes), then magnetic potential or electric potential of the each node under certain boundary conditions and initial conditions can be calculated according to magnetic vector potential and electric scalar potential.

TABLE 1 THE STRUCTURAL PARAMETERS OF MAGNETIC SUSPENSION SPHERICAL RELUCTANCE MOTOR

the radius of spherical top of stator salient pole/mm	51
unilateral air gap of between stator surface and rotor surface/mm	1
the radius of outside spherical surface of rotor/mm	50
the radius of inner spherical surface of stator/mm	20
the radius of outside spherical surface of stator/mm	38
the length of air gap/mm	1
the number of stator groove	6
the number of groove in rotor latitude direction	7
the number of groove in rotor longitude direction	12
the number of stator coil	50
polar altitude of stator/mm	25
coil current/A	1

Based on magnetic potential and electric potential, we can get other physical quantities of electric field such as the

distribution of line of magnetic force, magnetic induction, electric displacement flux, energy of electromagnetic field, magnetic force, torque, inductance, capacitance and so on through dealing with the solution. Due to the symmetry of structure of magnetic suspension spherical reluctance motor ,only one stator and rotor are choosed to research and start the model.The structural parameters of magnetic suspension spherical reluctance motor are showed in Table 1. The grid of motor is showed in Fig.2(there are no air and winding parts).The grid pattern of rotor is partly showed in Fig.3.

In Fig.2 and 3,the unit after meshing of solid modeling is showed. Thanks to having magnetic leakage in air, the practical calculation is performed outside the whole model including the air.

All physical units in model choose tetrahedral unit SOLID98 having 10 nodes(with a view to geometry irregularity of magnetic suspension spherical reluctance motor),and boundary units of the air choose tetrahedral unit INFIN47 having four nodes.^[8]When meshing, it should be taken into account that air gap between stator and rotor is a position that the variation of magnetic field is large, so grid density should be relatively close. Considering geometry symmetry of motor, both sides of stator salient pole satisfy half a cycle boundary conditions in the range of the stator and rotor relative a polar distance. On other boundary face, lines of magnetic force and boundary surface is considered to be parallel and internal boundary conditions of motor can meet itself.^[9]

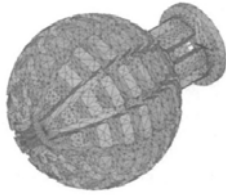


Fig.2 Motor meshing map

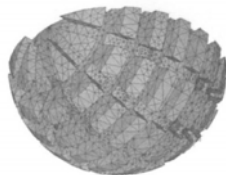


Fig.3 Rotor meshing map

C. Calculated Results

By using ANAYS , a plane where it is in the air gap between rotor salient pole and stator salient pole twined by coils is intercepted , then we can figure out magnetic flux through this plane.^[10-11]In this paper, we will figure out the magnetic flux through this plane, when the rotor of magnetic suspension spherical motor per rotates 1° around z-axis.^[12-13]

It is shown in Fig.4 that variation curves of the magnetic flux density of the section which is in the air gap between part of the stator pole and rotor salient pole along with the variation of rotor rotation angle in different stator current, The paper sets the situation that stator salient pole axis coincides with rotor concave pole axis to 0° .In Fig.4, when stator salient pole axis coincides with rotor concave pole axis, the number of magnetic flux produced by stator core which goes into rotor salient pole magnetism gathering structure is largest, at this moment, magnetic flux density of the air gap is largest. With rotor salient pole straying from the central position of stator salient pole axis, the leakage magnetic flux of

the motor becomes larger, and the magnetic flux density of section where it is in the air gap becomes smaller and smaller. But when it enters into the next magnetic pole, the magnetic flux density of section starts to become larger again.

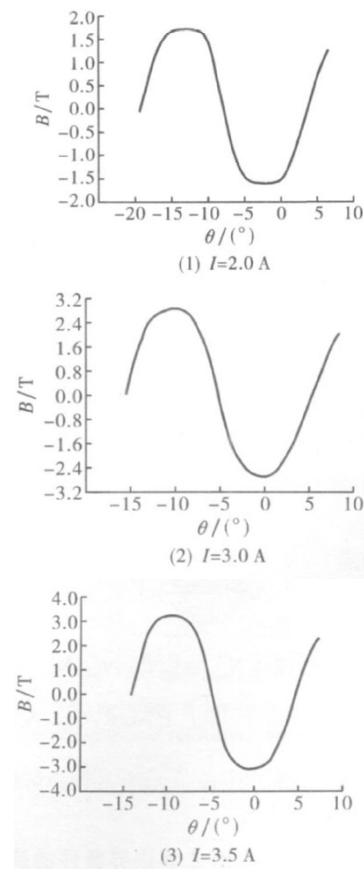


Fig.4 Magnetic flux density curve

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