The Simulation of Electromagnetic Suspension System Based on the Finite Element Analysis

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Abstract—In this article, the large air gap electromagnetic suspension system model is accurately divided into the mesh by the method of the finite element analysis, then the electromagnetic force of the suspended matter in the system is calculated. Finally, the fitting curves of the experimental data of a new kind of distributed electromagnetic array system can be obtained through the least squares method and the fitting expressions of different model system in the large air gap are achieved.

Index Terms—electromagnetic suspension system; finite element analysis; large air gap

I. INTRODUCTION

The finite element analysis method is a numerical method solving the numerical and physical boundary value approximately. Its development experience is consisted of Node Finite Element Method (N-FEM) and Edge-Based Finite Element Method (EB-FEM). The so-called Node Finite Element Method uses scalar interpolation function as a base function, but the great inconvenience of dealing with conductor and medium edge horn is the biggest weakness of this method. Thus the vector finite element method is proposed, which gives the freedom to the edge instead of node.

The core idea of finite element is the discretization of the structure. Firstly, a real structure is imaginarily discretized into a finite number of inerratic combination units. Secondly, the physical parameters of the actual structure can be calculated by the analysis of the discrete body. Finally, the approximate result that meets the engineering accuracy is obtained and replaces the analysis of the actual structure. As one of the popular advanced technology in recent years, the technology research is receiving more and more attention [1] [2] [3].

In this paper, several kinds of mathematical models of the large air gap electromagnetic levitation system have been given. On the basis of the theory of finite element analysis and the Maxwell’s equations, the space magnetic field intensity is analyzed and calculated. The finite element analysis is applied to the electro-magnetic suspension technology, and we get the space magnetic field intensity and calculate several change trends of electromagnetic force under the large air gap. Finally, the method of least squares is used to get the relevant fitting mathematical expressions.

II. THE FINITE ELEMENT ANALYSIS THEORY AND ELECTROMAGNETIC SUSPENSION SYSTEM

A. The Finite Element Analysis Theory

The finite element analysis method is a numerical method based on variation principle approximate interpolation and discretization. Firstly, the boundary value problem to be solved is converted into the corresponding variation problem and the variation problem is converted into the extremal problem of general multivariate function. Finally, an algebraic equation is obtained, the solution of which is a numerical solution.

The most important step of the finite element analysis is the regional discretization, which will influence the computing time, the requirements of computer memory and the numerical results precision. For the three dimensional (3D) problem, the most common unit is the tetrahedron which is the simplest and most suitable for discrete arbitrarily volume area, as shown in Fig. 1.

After discretization of the volume area, a suitable basis function is needed to approximately express the unknown functions in each unit which mainly includes Node Finite Element Method (N-FEM) and Edge-Based Finite Element Method (EB-FEM) (which is commonly used now). For the vector function \( w_{i,j} \), we have

\[
 w_{i,j} = \lambda_j \nabla \lambda_i - \lambda_i \nabla \lambda_j
\]
where \(i, j\) are the vertexes. Since a tetrahedron has four vertexes, the volume coordinates of the tetrahedron can be described as
\[
\lambda_i = a_i + b_i x + c_i y + d_i z
\]
where
\[
\begin{bmatrix}
b_1 & c_1 & d_1 & a_1 \\
b_2 & c_2 & d_2 & a_2 \\
b_3 & c_3 & d_3 & a_3 \\
b_4 & c_4 & d_4 & a_4 \\
\end{bmatrix} = \begin{bmatrix}x_1 & x_2 & x_3 & x_4 \\
y_1 & y_2 & y_3 & y_4 \\
z_1 & z_2 & z_3 & z_4 \\
1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

\[
\lambda\nabla \cdot = \nabla \times = \nabla \times \nabla
\]

Fig. 1.

Tetrahedron unit of the finite element division

The following result can be obtained
\[
\nabla \cdot w_{i2} = 0, \quad \nabla \times w_{i2} = 2V \lambda_i \nabla \lambda_i
\]

Assume that \(e_i\) represents a unit vector from node 1 to node 2, \(\lambda_{i1}\) is the linear function that changes from 1 (node 1) to 0 (node 2) and \(\lambda_{i2}\) is the linear function that changes from 1 (node 2) to 0 (node 1), therefore
\[
e_i \cdot \nabla \lambda_{i1} = -\frac{1}{l_i}, \quad e_i \cdot \nabla \lambda_{i2} = \frac{1}{l_i}
\]

where \(l_i\) represents the length of the edge connecting nodes 1 and 2, so
\[
e_i \cdot w_{i2} = \frac{\lambda_{i1} + \lambda_{i2}}{l_i} = \frac{1}{l_i}
\]

It means that \(w_{i2}\) has a constant tangential component along the edge (1, 2). As a vector base function of an edge field related to the edge (1, 2), \(w_{i2}\) has all the necessary features. If the edge is defined as edge 1, we have
\[
N_i = w_{i1} l_i = (\lambda_i \nabla \lambda_i - \lambda_i \nabla \lambda_i) l_i
\]

Similarly, the vector base function of the edge \(j\) is described as below
\[
N_j = w_{j1} l_j = (\lambda_j \nabla \lambda_j - \lambda_j \nabla \lambda_j) l_j
\]

where the definitions of edge number, node \(i\) and node \(j\) are shown in Fig. 1 and Table I.

So the vector field of the unit can be divided into
\[
E^r = \sum N^r_i E^r_i
\]

where \(E^r\) represents the field of the unit, \(N^r_i\) represents the vector base function of the unit and \(E^r\) represents the tangential fields along the edge \(i\).

TABLE I.

<table>
<thead>
<tr>
<th>Edge (i)</th>
<th>Start node (i_1)</th>
<th>End node (i_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The final results of finite element formula is a group of linear equations, which can be described as
\[
a_{i1} x_1 + a_{i2} x_2 + a_{i3} x_3 + \ldots + a_{in} x_n = b_i
\]

\[
a_{j1} x_1 + a_{j2} x_2 + a_{j3} x_3 + \ldots + a_{jn} x_n = b_j
\]

\[
\ldots
\]

\[
a_{m1} x_1 + a_{m2} x_2 + a_{m3} x_3 + \ldots + a_{mn} x_n = b_m
\]

which can be reduced as
\[
Ax = b
\]

where \(A\) is a coefficient matrix of size \(n \times n\), \(x\) is an unknown quantity and \(b\) is a known vector. For 3D electromagnetic field problem, the dimension of the coefficient matrix \(A\) increases rapidly with the increase of solving region and \(A\) is a sparse matrix.

B. The Basic Principle of Electromagnetic Suspension System

The edge method is used to solve the static magnetic field, which is using the freedom of division on the unit. The basic Maxwell’s equations of 3D static magnetic field are shown as follow
\[
\nabla \cdot H(x, y, z) = J(x, y, z)
\]

\[
\nabla \times B(x, y, z) = 0
\]

\[
B = \mu H
\]

where \(B(x, y, z)\) is the magnetic flux density, \(H(x, y, z)\) is the magnetic field intensity and \(J(x, y, z)\) is the current density. The third equation describes the constitutive relationship between magnetic field intensity and the magnetic flux density, where \(\mu\) is the dielectric magnetic permeability. The cylindrical coordinate system and the magnetic vector potential \(A\) are brought in for the axisymmetric problems [4] [5].

The magnetic flux density of the permanent magnet is described as
\[
B = \mu_0 \mu H + \mu_0 M_p
\]

where \(\mu_0 = 4\pi \times 10^{-7} \text{H/m}\) is the magnetic permeability in absolute vacuum, \(\mu_0\) is the relative magnetic permeability and \(H_p\) (M) is the intensity of polarization of the permanent magnetic material.

The number of the degrees of freedom to be solved on the tetrahedral partition adopted is up to 10, four are the magnetic scalar potential on the four vertices of
tetrahedron, the other six are the magnetic flux densities of the six sides of tetrahedron. The method of quadratic interpolation is used to approximate the field quantity in a single division.

The electromagnetic force equation is

$$B_i(i, \delta) = \frac{\Phi_i(i, \delta)}{S_{i}^{\delta}} = 0.5\mu_{c}C_{\phi}N_{i}i(t)S_{i}^{\delta}(\delta)\left(\int_{\delta}^{\delta_{i}} S_{i}^{\delta}(\delta')d\delta'\right)^{-1}$$  \hspace{1cm} (14)

where $C_{\phi}$ is the magnetic flux leakage coefficient, which has relations with the leakage magnetic flux $\Phi_i$; $S_{i}^{\delta}$ is the magnetic flux equivalent area function, which has relations with $\delta(t)$.

Suspension suffered electromagnetic attraction is

$$F_{e}(z, i) = \frac{B_{i}^{2}A}{\mu_{0}} = \frac{\mu_{0}A_{N}^{2}}{4}\int_{z}^{z_{i}}(t)$$  \hspace{1cm} (15)

where $F$ is the levitation force (N) of each electromagnet; $A$ is the area of permanent magnet (cm$^2$); $B$ is the magnetic field strength (T).

C. Model

Electromagnetic suspension system makes use of the repulsion between the electromagnetic coils and the permanent magnets in the space, which can provide enough electromagnetic levitation force for offsetting the gravity of the suspended.

III. THE ANALYSIS OF THE SINGLE ELECTROMAGNETIC SUSPENSION SYSTEM

According to the analysis above, the model of the electromagnetic levitation system is established. As one of the most important factors for the electromagnetic levitation force, the air gap is analyzed and studied, model specific parameters are shown in the Table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Permanent magnet radius</th>
<th>Permanent magnet thickness</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>$R$/mm</td>
<td>$T$/mm</td>
<td>$I$/A</td>
</tr>
<tr>
<td>Value</td>
<td>350</td>
<td>20</td>
<td>16000</td>
</tr>
<tr>
<td>Parameter</td>
<td>Electromagnet core radius</td>
<td>Electromagnet core thickness</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>$R$/mm</td>
<td>$T$/mm</td>
<td></td>
</tr>
<tr>
<td>Value</td>
<td>275</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

The finite mesh dissection of the single electromagnetic suspension model can be made through the finite element method, and the results are shown in Fig. 2. Other conditions remain unchanged, the working environment is air and the air gap size changes from 0 m to 4 m. Fig. 3 shows the magnetic field distribution of the electromagnetic suspension system and the date of electromagnetic force is shown in Fig. 4.

In order to explore the rules of the electromagnetic levitation system under the large air gap, the least square method is used in data fitting. Compared to other data fitting method such as interpolation method and approaching function method, the least square method works better [6] [7]. The base functions that can be selected in the least square method are various, such as the common polynomial, Chebyshev polynomial, Bemstein polynomial, etc. According to the electromagnetic field theory formula, the least square method is used in data fitting based on the rational fitting function, The fitting formula is

$$f(x) = 0.2259x^2 + 653x^{-1} - 308.5$$  \hspace{1cm} (16)

Fig. 4 shows the fitting graphics. From the fitting formula we can see that the second item coefficient of the
formula is small while the first item coefficient is large, they are different from the theoretical formula. Because during 2-4 meters, the electromagnet magnetic fields intensity produced by electromagnet in space is abate, the characteristics of magnetic field has changed.

IV. THE ANALYSIS OF THE DISTRIBUTED ELECTROMAGNETIC SUSPENSION SYSTEM

In order to be more close to requirements of real experiment, we increase the number of the research object.

Taking four-distribution array as an example, the original single electromagnet is divided into four small single electromagnets. Model geometry parameters are shown in the Table III.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Permanent magnet radius (R1/mm)</th>
<th>Permanent magnet thickness (T1/mm)</th>
<th>Current (I/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>350</td>
<td>30</td>
<td>18000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electromagnet core radius (R2/mm)</th>
<th>Electromagnet core thickness (T2/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>500</td>
<td>400</td>
</tr>
</tbody>
</table>

The finite mesh dissection of the distributed electromagnetic suspension model can be made and the result is shown in Fig.5. The magnetic field distribution of the electromagnetic suspension system is shown in Fig.6. The working environment is air and the suspension is 2m in height, moving the suspended matter along horizontal direction, we can observe the changing law of the electromagnetic force, the result is shown as below.

According to the electromagnetic field theory formulas, the data is fitted by the least square method. Fig. 7 shows the fitting curve of the axial electromagnetic forces that changed with the horizontal displacement. The fitting formula is

\[ f(x) = -41.05x^2 - 6.244x - 99.77 \]  \hspace{1cm} (17)

Fig.8 shows the fitting curve of the lateral electromagnetic forces which responds with the horizontal displacement. The fitting formula is

\[ f(x) = -24.25x^2 - 71.39x + 0.1023 \]  \hspace{1cm} (18)

In the distributed system model, the axial force change formula mainly presents the decline of the parabolic tendency, the second item coefficient is far bigger than
the first one; On the contrary, the second item coefficient of the lateral force change formula is less than the first one, which is closer to linear characteristics. The rule that electromagnetic force changes with the distance is inversely proportional to the distance, and the x here is just a part of the direct distance.

V. CONCLUSION

This paper analyzes the electromagnetic field of mixed suspension electromagnet with finite element analysis method. We model and analyze the suspension electromagnet to study the relationship between the electromagnetic force, current, and suspension gap. Then, the change law of the electromagnetic force with horizontal offset electromagnetic field is also studied. Then the calculated dates are fitted by the least square method. Finally, we compare the fitting formula with the theory one. These results lay the foundation for the further experimental study.

REFERENCES


Zhengfeng Ming (M’08) was born in Xi’an County, Shaanxi Province, China. He received the B.S. degree in automatic control from Xi’an University of Technology, Xi’an, China, in 1988, the M.S. degree in the industrial electrical automation from Xi’an Science University, Xi’an, in 1993, and the Ph.D. degree in electrical engineering from Xi’an University of Technology, in 2002.

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