Computer Simulation Study on Optimization of Linear Servo Motor Used in CNC Machines

Zhang Yuqiu, Yu Minghu, Ye Yunyue, Liu Xiao,
College of Electrical Engineering
Zhejiang University
Hangzhou, China
Email: tangshanzyq@yahoo.cn; huhuminghu@163.com; yeyunyue@yahoo.com.cn; mrluxiao@yahoo.com.cn;

Abstract—For computer numerical control (CNC) machine tools, the double side air-cored permanent magnet linear servo motor (DAPMLSM) is suitable for high-speed and high-precision servo feed systems. But it also has thrust ripple caused by non-sinusoidal magnetic field distribution. Finite element analysis (FEA) was used to study motor characteristics, and the computer simulation results match well with the prototype data. It indicates FEA method is accurate. Based on that, the influences of DAPMLSM main structure dimensions were analyzed. The air-gap and magnet thickness mainly affect the amplitude, and the pole-arc coefficient affects both amplitude and its distribution. The distribution condition of the magnetic field in the air-gap could be improved effectively by optimal design of the pole-arc coefficient, furthermore the thrust fluctuations is reduced.

Keywords- permanent magnet; linear servo motor; magnetic field; finite element analysis; CNC machine tools

I. INTRODUCTION

In recent years, linear servo system is widely used in machine tools, semiconductor and electronics manufacturing, optical equipment, logistics, automation and other industries. Its major advantages are simple structure, high positioning accuracy, fast response, high sensitivity, and good dynamic characteristics [1][2]. Some of the world renowned machine-tool manufacturers in developed countries launched new direct drive computer numerical control (CNC) machine tools, such as Germany's DMG Inc., Japan Sodick Corporation, and the United States Anorad companies. Its efficiency can be increased by 20% -40%, increase 5 times accuracy [3]. Permanent magnet linear servo motor (PMLSM) uses high-energy permanent magnets. With high thrust density, low loss, small time constant, fast response and easy control, PMLSM has become the focus of linear servo motors [3][4].

The double side air-cored PMLSM(DAPMLSM) is very suitable for servo system due to its high dynamic performance, zero cogging and zero-gravity features[3]. But it also has thrust ripple caused by non-sinusoidal magnetic field. Therefore improving the sinusoidal distribution of magnetic field is very important work to improve the motor’s servos performance.

Finite element analysis (FEA) is a powerful tool to study motor characteristics, including magnetic field distribution, thrust, the deformation of the rotor, dynamic characteristics, and the motor's parameters. Also this kind method is applied in this paper in order to calculate accurately the no-load air-gap magnetic field, and the numerical computation is finished by Ansoft Maxwell. The prototype experiments indicate the FEA results are almost equal to the actual value. The influences of DAPMLSM main structure dimensions are analyzed by FEA, including the air-gap and magnet thickness and pole-arc coefficients. From it, some approaches to improve the sinusoidal shape of magnetic field are provided.

II. DAPMLSM OF CNC MACHINES

As shown in Figure1, DAPMLSM has two parts, stator (machine bed) and mover (machine table). Permanent magnets are mounted on two side walls inside the stator iron yoke, magnetized along the y direction. The polarity is shown in Figure 1. There is no normal force, reducing friction when the secondary movement and the requirements of linear guide installation. Coils are installed on the mover without core, to raise the efficiency of the motor and reduce the mover quality. When three-phase sinusoidal currents are injected to the coils, the mover and its load will move in x direction on synchronous speed. A straight line grating is fixed on its side, used to measure the displacement of mover. It’s very suitable for light loads and rapid response situations.

Figure 1. Topology of DAPMLSM (1. stator iron yoke;2. permanent magnets;3.coil;4.mover;5. air-gap)

The double side air-cored PMLSM experiment platform is shown in Figure 2, and the motor main dimensions are listed in TABLE I.

Figure 2. Prototype of PMLSM
Air-cored permanent magnet linear servo motor doesn’t have iron core, so there is no fluctuations caused by cogging effect. In order to reduce the thrust ripple and improve performance of servo motor, its flux density should be as close as possible to sinusoidal.

### TABLE I. MOTOR MAIN DIMENSIONS

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Value/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar pitch ( \tilde{T} )</td>
<td>22.5</td>
</tr>
<tr>
<td>Air-gap length ( \delta )</td>
<td>14.6</td>
</tr>
<tr>
<td>PM width ( T_m )</td>
<td>18</td>
</tr>
<tr>
<td>PM thickness ( h_m )</td>
<td>3.6</td>
</tr>
<tr>
<td>PM length ( l_m )</td>
<td>60</td>
</tr>
<tr>
<td>Back iron thickness ( h_i )</td>
<td>5.4</td>
</tr>
</tbody>
</table>

### III. NUMERICAL MODEL

Traditionally, the calculation method of motor performance is the equivalent circuit - magnetic method. But it's difficult to accurately take the saturation effect of ferromagnetic materials, cogging effect, skin effect, etc. into account, and can’t accurately calculate the motor actual current, magnetic field and torque waveform. With the development of computer technology, finite element analysis (FEA) system evolves to be able to simulate the actual various physical systems. It can overcome the shortcomings and make designers away from complex numerical algorithms, but focus on how to complete results analysis. It provides users with great convenience. ANSOFT Maxwell is a high-performance interactive software package that uses FEA to solve electric, magnetostatic, eddy current and transient problems. In this paper, Ansoft Maxwell software is used to analyze magnetic field of DAPMLSM.

#### A. FEA model

To simplify the analysis model and save computation time, assuming that motor has infinite z direction length, the motor no-load air-gap magnetic field to solve is reduced to two-dimensional constant magnetic field. The FEM model is built according to the geometric characteristic of the motor structure, which includes the back iron, permanent magnets (PMs), coils and problem region. Mover position does not affect the no-load magnetic field distribution in this motor.

Then access the Material Manager, assign iron to the back iron, assign copper to the coils, assign vacuum to the problem region. Add a new material N45SH using non-linear B-H curve, and assign it to permanent magnets. Set boundary conditions to balloon. Generate a new solution to calculate the magnetic field. Then it can mesh the model and solve itself as we defined.

After solving the problem, post-processing enable the motor magnetic motor designers have clear and intuitive understanding of the calculation results. Voluminous data can be change into various maps, curves, and tables, which are engineer familiar with.

Mesh is shown in Figure 3. , and the flux lines distribution is shown in Figure 4. We can obtain flux density at different distances from the air-gap center by draw non-model line in the air-gap. Prototype’s flux density in air-gap center is gained by LakeShore 421 Gaussmeter. It’s compared with 2DFEA results as shown in Figure 5. Finite element results are approximately equal to the measured values. It presents FEA method is verified correctly.

#### B. Harmonic analysis

In order to reduce the thrust ripple and improve performance of servo motor, its flux density should be as close as possible to sinusoidal curve. After gaining flux density distribution by FEA, next is to do harmonic analysis by MATLAB.

Harmonic analysis result is shown in Figure 6. The biggest one is the third harmonic. Take the ratio between the total harmonics and the fundamental component \( \frac{B_{1y}}{B_{1y}} \) as a standard measure of the air-gap magnetic field sinusoidal. Smaller the ratio is, more sinusoidal...
magnetic field is, and more stable the motor thrust is. For the prototype, the ratio is 10.96%.

![Figure 6. Harmonic of the prototype](image)

IV. OPTIMAL DESIGN OF DAPMLSM

In order to make servo motor thrust more stable and improve CNC machine tools machining quality, more sinusoidal air-gap magnetic field and more advanced control mode of the servo motor is needed. Through the optimal design of motor dimensions, designers can reduce the harmonic content and improve sinusoidal degree of flux density.

The polar pitch is defined by CNC machine speed desire. Then other dimensions can be changed by designers. Harmonic $B_{yv}$ is related to the three main dimensions, permanent magnet width $\tau_m$, thickness $h_m$ and air-gap thickness $\delta$. Define three factors, pole-arc coefficient $\alpha_p = \frac{\tau_m}{\tau}$, magnet thickness coefficient $\beta = \frac{h_m}{\tau}$ and air-gap thickness coefficient $\gamma = \frac{\delta}{\tau}$ to analyze the dimensions influence on the distribution of the magnetic field.

A. Pole-arc coefficient influence

Keeping $\beta$ and $\gamma$ unchanged, modifying the PMs’ width, $\alpha_p$ will change together. After 2DFEA, do harmonic analysis, smooth and draw the fitting curve next. The fundamental component $B_{y1}$ increases together with $\alpha_p$ as shown in Figure 7. The relationship between the third, fifth, seventh, ninth harmonic ratio $B_{yv}/B_{y1}$ and the pole-arc coefficient $\alpha_p$ is shown in Figure 8. Take the ratio between the total harmonics and the fundamental component $\sum B_{yv}/B_{y1}$ as a standard measure of the air-gap magnetic field sinusoidal. The relationship between $\sum B_{yv}/B_{y1}$ and $\alpha_p$ is shown in Figure 9. It shown that when $\alpha_p$ is between 0.6 and 0.8, $B_{y1}$ is big enough and the total harmonic ratio is smaller than 0.1. So $\alpha_p$ should be 0.6~0.8 in motor design work.

![Figure 7. Relationship between $B_{y1}$ and $\alpha_p$](image)

![Figure 8. Relationship between $B_{yv}/B_{y1}$ and $\alpha_p$](image)

![Figure 9. Relationship between $\sum B_{yv}/B_{y1}$ and $\alpha_p$](image)

B. Magnet and air-gap thickness coefficient influence

Keeping $\alpha_p$ unchanged, modify the PMs and air-gap thickness separately. The relationships between $B_{y1}$, $\sum B_{yv}/B_{y1}$ and $\beta$ are shown in Figure 11 and Figure 13. Both the fundamental component and the total harmonic ratio are $\beta$’s monotone increasing functions. With $\beta$
increases, the air gap magnetic field fundamental component will increase, and the harmonic ratio will increase too. Meanwhile, the relationships between $B_{y1}$, $\sum B_{yv}/B_{y1}$ and $\gamma$ are shown in Figure 12. and Figure 13. Both the fundamental component and the total harmonic ratio are $\gamma$’s monotone increasing functions. The total harmonic ratio is $\gamma$’s reduction function. The air gap magnetic field fundamental component and harmonic ratio will increase with $\gamma$ decreases.

In general design, to improve the motor thrust density, a larger flux density is needed. Increasing magnet thickness and reducing air-gap thickness is a usual means of increasing flux density as shown in Figure 10. and Figure 12. It also reduces the air gap magnetic field distribution sinusoidal as shown in Figure 11. and Figure 13. at the same time. But the influences are smaller than the pole-arc coefficient influence on the sinusoidal degree of magnetic field. So in the motor design, the main influence of $\beta$ and $\gamma$ should be changing the amplitude. And the optimization of magnetic field distribution is mainly completed through optimizing the pole-arc coefficient to reduce the harmonic content.

V. CONCLUSIONS

FEA of PMLSM is based on complex geometrical model, considering the nonlinear characteristics of magnetic materials and boundary conditions for numerical calculations. Through post-processing, magnetic field distribution, motor thrust and normal force characteristics can be calculated. Comparison with prototype data indicates FEA has a very high precision. Analysis and design of PMLSM, based on numerical FEA, have important reference value and significance.

In this paper, Ansoft software based on FEA is used to optimize the structure dimensions of the DAPMLSM, in order to obtain a more sinusoidal magnetic field. The results indicate that the motor air-gap and permanent magnet thickness mainly affect the amplitude of flux density. The pole-arc coefficient affects significantly both the amplitude and harmonic content of the magnetic field. When it is 0.6~0.8, a more sinusoidal magnetic field distribution can be obtained. Then the thrust fluctuations, caused by magnetic field non-sinusoidal distribution, will be reduced, and the quality of table processing can be improved. It’s significant to achieve high-speed and high-precision servo feed systems.

ACKNOWLEDGMENT

Thanks to Dr. Liu Xiao and Professor Ye Yunyue providing useful guidance. This work was supported by a grant from the National Natural Science Foundation of China (No.50905160). Email of correspond author Mr. Liu Xiao is mrliuxiao@yahoo.com.cn.
REFERENCES


