Harmonic Analysis of Magnetic Field Measurement of Maglev Plane Motor

Xu Wenru1, Zhang Shengguo1,2*, Hu Weiwen1, Yang Jiawei1 and Hou Hao1

1 School of Electrical Engineering, Northwest Minzu University, Lanzhou, Gansu, 730030, China
2Key Laboratory of China’s Ethnic Languages and Information Technology of Ministry of Education, Northwest Minzu University, Lanzhou, Gansu, 730030, China
* Corresponding author’s e-mail: zhangshengguo@tsinghua.org.cn

Abstract. With the rapid development of production scale and technology level in the field of precision engineering technology, plane motor is a new type of motor which can directly output plane motion and has the characteristics of simple structure, high precision and fast response speed. In this paper, the magnetic levitation plane motor (MLPM) as the research object, it is a hot research and development in recent years, MLPM has a good application prospect in driving advanced manufacturing equipment used under high vacuum conditions. In this paper, the harmonic characteristics of magnetic levitation plane motor are analyzed by establishing the analytical model of each odd harmonic. The actual magnetic field of the permanent magnet array is measured on the measuring platform of Tesla meter, and the measurement results are analyzed. And then the analytical data are compared with the actual field data. Further calculation shows that the maximum relative error between the simulated and measured results decreases gradually with the increase of the odd harmonic order of the magnetic field.

1. Introduction

Ultra-precision machining technology is one of the important development directions of modern manufacturing science, is the foundation of modern high-tech industry and science and technology development, is an important development direction of modern manufacturing science, its development level is also an important symbol to measure the level of science and technology of a country [1]. With the rapid development of information technology and its related industries, today's society has entered the information age represented by LSI technology. Lithography is the core step of LSI manufacturing process. Lithography machine, as an important equipment of lithography process, integrates optical, mechanical, electrical and other technologies, and its design and manufacturing embody the research results of the highest level in related disciplines [2]. The lithography process needs to be carried out in a vacuum environment, so the existing air float table can no longer meet the new process requirements.

Maglev flat motor (MLPM) is a hot research and development in recent years. MLPM has a good application prospect in driving advanced manufacturing equipment under high vacuum conditions. Maglev workbench is the core component of the next generation lithography machine. The study of the system is a necessary condition for realizing the strategic breakthrough of lithography machine in China and mastering the key technologies of extreme ultraviolet lithography. Maglev plane motor is the driving part of the magnetic levitation worktable. It is of great significance to study its related
technology.

The MLPM is composed of two parts, one is the stator, the other is the motor. The stator and motor are constructed in two ways: the first is composed of coil array and permanent magnet array stator; the second stator is permanent magnet array and coil array. No matter how MLPM is constructed, it is important to understand and learn this handy knowledge for better motion performance.

Based on the analysis of the odd order harmonics, this paper analyzes the synthesis of the odd order harmonics. Firstly, the plane motor is introduced briefly, the first order harmonic analytic model of HPMA magnetic field is analyzed, and the measurement system and measurement scheme are described. Finally, the analytical data and the measured data are compared and analyzed for a deeper understanding.

2. Magnetic field modeling of magnetic levitation plane motor

A model of the electromagnetic force and torque of a single iron-free coil in an HPMA magnetic field is shown in Figure1. Permanent magnets can be divided into large permanent magnets and small permanent magnets, and have a certain regular arrangement. Arrows indicate small magnetic poles pointing from the South Pole to the North Pole, and the symbols "o" and "+" mean the North Pole and South Pole of the large magnet [3]. Two coordinate systems, XYZ and $m_xm_ym_z$, are established. The X-axis and Y-axis of the XYZ coordinate system are perpendicular to the direction of the magnetic field. The other coordinate system is obtained by rotating the XYZ coordinate system 45° clockwise, which is the magnetic field reference coordinate system $m_xm_ym_z$. The harmonic flux density distribution of the analysis model is studied in the fixed coordinate system XYZ.

According to Maxwell's electromagnetic field theory, the effective flux density distribution is the sum of the harmonic components of the Fourier sequence. The first-order flux density (magnetic induction intensity) distribution of the magnetic field of HPMA can be described as:

$$B_m=(X,Y,Z)=[B_{mX},B_{mY},B_{mZ}]^T$$

$$B_m = B_{xy} \sqrt{2} e^{-\pi \tau Z} 
\begin{bmatrix}
-\sin \left(\frac{\pi}{\tau} X\right) \\
\sin \left(\frac{\pi}{\tau} Y\right) \\
\cos \left(\frac{\pi}{\tau} X\right) - \cos \left(\frac{\pi}{\tau} Y\right)
\end{bmatrix}$$

Where $B_{mX}$, $B_{mY}$ and $B_{mZ}$ are X, Y and Z direction components of the flux density distribution BM respectively; The effective amplitude of the first order harmonic of the flux density distribution in the XY plane when $B_{xy}$ is $Z=0$. Once the size of the HPMA is determined, $B_{xy}$ is a constant. $\tau$ is the distance between magnetic poles in the XYZ coordinate system.
3. Magnetic field measuring platform and measuring method
In order to verify the odd-order harmonic analytic model of magnetic field [4], the measurement system is established, as shown in Figure 2.

All measurements were made at the HPMA effective magnetic field area of 212 mm × 212 mm and magnetic pole spacing \( \tau = 10.6 \) mm. Mounted on a special X-Y plane. The sensor is mounted on the beam through the upper connecting plate. The adjusting mechanism can adjust the height of the sensor. The coil array shifter is connected to the sensor through the lower connecting plate. The Hall probe is mounted on the measurement and adjustment mechanism, and the Z direction can be adjusted with an accuracy of 0.1mm [5][6]. The sensor will be measured data after pretreatment, the data will be transmitted to the computer. The data sampling frequency of the measurement system is 250Hz.

4. On the influence analysis of high order harmonics
According to formula (1), we take \( B_{xy} = 0.896 \) Tesla, \( \tau = 10.6 \) mm, and the flux density distribution of the X component in the X direction at \( Z = 5.8 \) mm. Each odd analytic harmonic period is consistent with the
structure of HPMA. The period is $2\tau = 21.2\text{mm}$.

The actual magnetic field of the Halbach permanent magnet array is synthesized by the harmonic components of the Fourier sequence with odd order (the amplitude of even order is 0). Figure 3 shows the harmonic synthesis curves of the x-component in the x-direction of the two-dimensional magnetic field of the odd-order Halbach permanent magnet array.

From the odd harmonic component synthesis curve of the two-dimensional magnetic field in Figure 3, it can be seen that the odd analytical harmonic synthesis curves are sinusoidal wave distribution. Due to the inevitable installation error measurement system error between the probe measurement plane and the direction of the magnetic field, the x-direction component of the magnetic flux density distribution along the Y-axis fluctuates around a certain constant value. However, in the area with a width of about $2\tau$ around the permanent magnet array, the amplitude of magnetic flux density becomes significantly larger, which is obviously due to the influence of magnetic field edge effect. The magnetic flux density distribution is not affected by the magnetic field edge effect at different air gap heights [7]. Figure 4- Figure 5 shows the comparison of the simulated and actual measured waveforms.

![Figure 3](image-url)

Figure 3 Shows the harmonic synthesis curves of the x-component in the x-direction of the two-dimensional magnetic field of the odd-order Halbach permanent magnet array.
Figure 4 Comparison of fundamental and measured waveforms.

Figure 5  (a) 1,3,5,7 odd harmonic superposition and measured waveform comparison; (b) 1,3,5,7,9 odd harmonic superposition and measured waveform comparison.

The magnetic flux density distribution is not affected by the magnetic field edge effect at different air gap heights. Since both the simulated value and the actual measured value are sinusoidal, we use the root mean square error to measure the error.

\[
E_{\text{rms}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (V_{mi} - V_{ti})^2}
\]  

Where, \( E_{\text{rms}} \) is the root mean square error, \( V_{mi} \) is the simulated value, \( V_{ti} \) is the measured value, and \( i \) is the number of points of the measured data. Under the same air gap height and different odd-order harmonic synthesis, the root mean square errors of magnetic field simulation results and measured
results are shown in the table below.

| Odd harmonic superposition | Root mean square error between measured data and simulated data (Tesla) |
|----------------------------|-------------------------------------------------------------------|
| 1 order                    | 0.0034665                                                         |
| 1 order + 3 order          | 0.0028179                                                         |
| 1 order + 3 order + 5 order| 0.0027625                                                         |
| 1 order + 3 order + 5 order| 0.0027639                                                         |
| 1 order + 3 order + 5 order| 0.0027639                                                         |
| 1 order + 3 order + 5 order| 0.0027639                                                         |

Further calculation shows that the maximum relative error between the simulated and measured results decreases gradually with the increase of the odd harmonic order of the magnetic field. When the magnetic field harmonic order is 9, the error is reduced to $27.639 \times 10^{-4}$ Tesla which is negligible. The above analytical model of magnetic field does not include the edge effect of magnetic field. In the application of moving coil magnetic suspension plane motor, the influence of edge effect of magnetic field can be avoided by increasing the magnetic field area [8].

Assuming that the measurement velocity is $V$ when measuring the magnetic field, according to Equation (1), the $x$-direction component of the flux density distribution at any time $t$ can be expressed as

$$B_{mx} = \frac{B_0}{\sqrt{2}} \sin \left( \frac{\pi}{\tau} vt \right)$$

The frequency of the first harmonic is expressed as

$$f_1 = \frac{V}{\tau}$$

The frequencies of each odd-order harmonic component are respectively

$$f_n = (2n+1)f_1$$

Where $n$ is a natural number.

5. Conclusion

On the measuring platform of Tesla meter, the actual magnetic field of permanent magnet array is measured, and the data of the actual magnetic field is analyzed and processed. The magnetic field contains different odd-order harmonics, and the amplitude of these harmonics will decrease with the increase of the harmonic order of the magnetic field. With the increase of the odd harmonic order of the magnetic field, the maximum relative error between the simulation results and the measured results decreases gradually. When the magnetic field harmonic order is 7, it can be ignored. These harmonic characteristics play an important role in the design of the closed loop control system of planar maglev motor.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 52065060).
References

[1] Yuan, J.L., Zhang, F.H., Dai, Y.F., (2010) Research on the development of science and technology in ultra-precision machining field. Journal of Mechanical Engineering, 46:161-177.

[2] Peng, Y.F., Yuan, B., Cao, X.Q., (2010) Current status and development trend of lithography. Optical Instruments, 32:80-84.

[3] Cho, H.S, Jung, H.K. (2002) Analysis and design of synchronous permanent magnet planar motors. Energy Conver, 17:492-499.

[4] Zhang Xinhua, Design and Control of Moving Coil Maglev Permanent Magnet Plane Motor. Jiangsu University. 2017.

[5] Zhang, S.G., Zhang, S., Liu, W.C. (2015) Harmonic Analyses with Measuring Electromagnetic Forces and Torques for Magnetically Levitated Planar Motors. In: International Conference on Advances in Energy and Environmental Science. Da Qing. 350-356.

[6] Zhang, S.G., Dang, X.P., Wang, K., (2013) Modelling of electromagnetic force/torque for magnetically levitated planar motor. Applied Mechanics and Materials, 2013:311-316.

[7] Zhang, S.G., (2014) Field Verification of Magnetic Field Analytical Model of Permanent Magnet Array. In: Wuhan, S., Jie, Z., Xiangping, Y., Juan, L. (Eds.), Magnetic Levitation Single Machine Drive and Control Technology. Science Press, Beijing. pp.35-36.

[8] Zhang, S.G., (2014) Field Verification of Magnetic Field Analytical Model of Permanent Magnet Array. In: Wuhan, S., Jie, Z., Xiangping, Y., Juan, L. (Eds.), Magnetic Levitation Single Machine Drive and Control Technology. Science Press, Beijing. pp.35-36.