Study on the magnetic decoupling method of magnetic levitation support for interference spectrometers

Ding Chao

Wuhan Digital Engineering Institute, *Wuhan, Hubei, 430205,mmt@cssc709.net*

Abstract – Interferometer spectrometer can change the optical path difference of lensby the constant motion of moving mirror, and optical path difference is used for qualitative and quantitative analysis of the function, so keeping uniform velocity and stability in the motion of the moving mirror has a great influence on accuracy and resolution of the spectrometer. In this paper, magnetic levitation device is used as the supporting system of the moving mirror, the motor of the voice coil is the driving system of the moving mirror and we studied the coupling between the two systems of controling the moving mirror. We support a method to analyze the magnetic field in moving mirror system, and decouple the current in the supporting system and driving system. The results show that the control current obtained by this method can effectively control the motion of the moving mirror and keep the moving mirror in a constants peed and stably during the movement.

I. INTRODUCTION

The realization of the qualitative and quantitative analysis function of the interference spectrometer depends on the change of optical path difference[1]. The optical path difference can be changed by the continuous movement of the moving mirror. It requires the moving mirror to have high-precision uniform speed and small swing in the vertical direction in the scanning process, which puts forward high requirements for the mechanical accuracy and system stability of the instrument.

The moving mirror is required to be stable and uniform in the process of motion in the interference spectrometer. However, in the design of the interference spectrometer, it is found that the system moving mirror inevitably has the problems of unstable motion under the traditional driving method[2]. Modern high-precision machining has been able to produce mechanical bearings to ensure the smooth movement of the interferometer[3]. In the early stage of

Nicolet company, the suspension torsion type wear-free mechanism was adopted[4]. The cantilever can swing around the shaft, and the moving mirror can move forward and backward in a straight line; The wedge-shaped beam splitter interferometer of Analect company can obtain coherent light only by moving the wedge-shaped compensation plate made of pure KBr back and forth, and the mechanical bearing is used for moving; Perkin Elmer has developed the variable angle swing interferometer[5]. It eliminates the moving mirror which is supported on the air bearing in a straight line in the classical interferometer. Although the air bearing is removed, all kinds of improved interferometers mentioned above can only be used in low resolution instruments. Rotating motor mechanical transmission, electronically controlled pneumatic hydraulic system and electromagnetic drive system are usually uesed as moving mirror drive system[6]. However, mechanical elements are prone to elastic deformation, friction, reverse clearance, non-linear error and other defects. And the vibration and tilt of the electro-controlled pneumatic hydraulic system are small, but it is slow and complex, also needs a gas and liquid supply system, which is not conducive to the miniaturization of the instrument[7]. These mechanical elements are also environmentally aware devices, so it is very difficult to meet test conditions. In conclusion, this study focuses to reduce the gravity of the moving mirror system and ensure that the moving mirror drive system is small in size, simple in control and high in precision.

In view of this phenomenon, we study the moving mirror driving system of the interference spectrometer, then design the magnetic suspension moving mirror support system with voice coil motor to make the moving mirror stable and uniform[8]. However, the magnetic field of voice coil motor and moving mirror are in the same system.The coupling of the magnetic force on the moving mirror affects the solution of the force results of the moving mirror in the horizontal and vertical directions, and can not control the moving mirror effectively. Therefore, we decouple the coupling magnetic force and accurately solves the force of the moving mirror, so that the moving mirror can maintain a uniform speed in the motion process. This high-precision and real-time method meets the requirements of uniform moving mirror of

interferometer in interference spectrometer.

II. STRUCTURE AND PRINCIPLE OF MOVING MIRROR SYSTEM

A. Structure and principle of magnetic suspension support system for moving mirror

We use voice coil motor as the driving system of moving mirror and magnetic suspension device as the support system of moving mirror. The magnetic suspension system is supported by a graphite sleeve. There are graphite bearing and moving mirror which is driven by a voice coil motor slides in the glass sleeve. The flexible graphite system is made of natural flaky graphite which is processed by special chemical treatment and heat treatment. So the components made by it do not contain any binder, maintain the original characteristics of natural graphite, and have good sealing performance, which can reduce the friction between components. Taking advantage of these characteristics of graphite, we designed a moving mirror support device with a magnetic levitation moving mirror combined with graphite glass bearings, as shown in Figure 1:
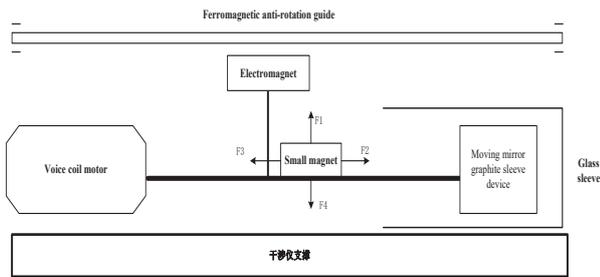

Fig. 1. Stress analysis of the drive system of moving mirror

In Figure 1, the voice coil motor and the moving mirror are connected by a graphite bearing, supported by a glass sleeve, and the graphite bearing is located in the glass sleeve. The electromagnet above the voice coil motor generates attractive force to the small magnet, which offsets the gravity of the graphite device of the moving mirror.It can make the graphite bearing basically no pressure on the glass sleeve. The magnetic action between the small cylindrical magnet and the ferromagnetic anti-rotation rail ensures that the moving mirror does not rotate when it moves, making it guided. When the voice coil motor driving mirror slides inside the glass sleeve, it is mainly used to balance the horizontal force of the electromagnet on the small magnet.The specific force analysis is as follows:

In Figure 1, F_4 is mainly generated by the gravity of the entire system, F_1 is the vertical component of the electromagnetic force generated by the upper electromagnet to the small magnet, F_3 is the frictional resistance and the electromagnet pairing during the movement of the moving mirror The resultant force of the horizontal force of the magnet, F_2 is the driving force generated by the motor. Adjusting the position of the

small magnet properly so that the graphite bearing and the moving mirror device are in a suspended state under the force of the electromagnet, reducing the friction of the graphite bearing and the moving mirror during movement. In the calculation process, it can be approximately considered that all the force at this time is provided by the horizontal force of the electromagnet on the small magnet. The force balance equation of the system is as follows:

$$F_4 = F_1 \tag{1}$$

After the moving mirror starts to move, in order to keep the device in a constant motion state, the driving force of the voice coil motor is equal to the horizontal component of the electromagnet to the small magnet. At this time, the force balance equation satisfied by the system is:

$$F_2 = F_3 \tag{2}$$

After satisfying the above two formulas, the system can reduce the friction of the system due to gravity and make a uniform linear motion in the horizontal direction.

B. Structure and principle of driving system of the moving mirror

In this system, we use a moving coil linear motor to drive the movement of the moving mirror[9]. The mechanism diagram of the voice coil motor is shown in Figure 2[10]:
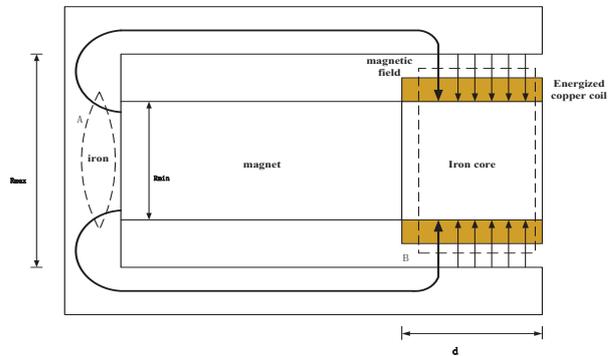

Fig. 2. The structure of voice coil motor

When the voice coil motor is working normally, the electromagnetic force generated can be calculated by formula (3) :

$$F = NBIL \tag{3}$$

In the formula:
N: Turn Ratio;
B: Magnetic induction intensity of the space where the coil is located, in T;
I:The current in the coil conductor, in A
L:Average effective length of coil conductor per turn in magnetic field, in m;
As long as the electromagnetic force on the coil is greater than the static friction resistance on the coil bracket, the coil can move in a straight line.

Due to the special design structure of the voice coil motor, the magnetic field of the moving coil can be regarded as uniform, and the friction force on the coil support is very small, so the static friction force can be considered as 0[11].

According to the equivalent magnetic circuit model, it can be considered that the magnetic flux generated from the surface of the magnet is equal to all the magnetic flux in the plane passing through the air gap of the coil[12]. That is to say, the magnetic fluxes of the surface A and the surface B enclosed by the dotted line in the figure 2 are equal, and the formula (4) (5) (6) can be obtained:

$$2\left(\pi \times \frac{R_{max} + R_{min}}{2}\right)d \times B_0 = \pi R_{min}^2 \times B \quad (4)$$

$$NBIL = F \quad (5)$$

$$L = 2\pi R_{min} \quad (6)$$

Therefore, substituting actual data into formula (4) (5) (6), the magnitude of the magnetic force on the coil can be obtained.

III. COUPLING PROBLEM AND DECOUPLING METHOD IN MAGNETIC SUSPENSION SUPPORT

The moving mirror system described in this article includes a horizontal drive system and a vertical magnetic levitation system. The small magnet connected to the moving mirror is in the force fields of the two systems, so the force received by the small magnet has coupling problems, which makes it impossible to achieve smooth control of the moving mirror by controlling the two systems.

It is considered that the magnetic force of the electromagnet on the small magnet in the vertical direction is equal to the gravity of the small magnet from the analysis of the motion effect.However, the electromagnet is fixed at the upper left corner of the small magnet, and the component force of the small magnet in the horizontal direction changes continuously with the movement of the small magnet in the horizontal direction. It is required the voice coil motor that controls the horizontal movement of the small magnet to always generate a Balance the changing driving force of this component.How to solve the current size of the voice coil motor so that the moving mirror keeps moving at a constant speed without any force in the vertical direction is the process of decoupling[13], which is also the problem that this article focuses on. Since the distribution of the magnetic field around the electromagnet is more complicated and cannot be calculated according to the simple Lorentz force solution method[14], using finite element analysis software to calculate the magnetic field generated by the electromagnet around the small magnet.Then Analyzing the force of the small magnet by applying different currents to the electromagnet at each

sampling point. The displacement of the small magnet and the function relationship between the electric current flowing through the electromagnet and the force of the small magnet in the vertical and horizontal directions can be obtained.

It can be known that the force of the electromagnet on the small magnet F_1 is related to the current flowing through the electromagnet I_1 and the location of the small magnet X . Therefore, the horizontal force applied by the electromagnet to the small magnet is:$\alpha F_1(I_1, X)$;The force of the electromagnet on the small magnet in the vertical direction is:$\beta F_1(I_1, X)$.

Since the coil of voice coil motor is also affected by the internal magnetic field of the motor, the force of the coil is analyzed by using the magnetic circuit theorem[15].

F_2 represents the force of the voice coil motor on the small magnet, and I_2 represents the current that controls the voice coil motor. $F_2(I_2)$ represents the force applied by the voice coil motor to the small magnet; G represents the gravity of the device;

Therefore, the process of solving the voice coil motor current I_2, can be expressed as:

$$\beta F_1(I_1, X) = G \quad (7)$$

According to (7) and the function relation obtained by software, the I_1 and $\alpha F_1(I_1, X)$ can be obtained.

Therefore, the decoupling process is completed. According to the formula (8) and the function obtained by simulation, the current of the voice coil motor can be obtained,

$$\alpha F_1(X, I_1) = F_2(I_2) \quad (8)$$

Therefore, the current of voice coil motor is obtained, and the decoupling process is completed according to formula (8) and the function relationship.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Firstly, the model of electromagnet and small magnet is established in ANSYS Maxwell. Considering the actual situation of the spectrometer, the movement stroke of the small magnet is set as 6 mm[16], and the position sampling is set to measure every 0.5 mm. Due to the accuracy of the control, the current range of the electromagnet coil is set to 0 ~ 1 A, and the measurement is conducted every 10mA. In this way, there are 1313 data points in the model of electromagnet and small magnet. The relationship between the force of the small magnet and the position of the small magnet and the current of the electromagnet can be obtained by fitting the surface of these data points with the sftool tool of MATLAB.

The functional relationship obtained is as follows:

$$\alpha F_1(X, I_1) = -6.028 - 0.04174X - 0.003224I_1$$
$$+ 0.02653X^2 - 0.001276X^3 \quad (9)$$

In the horizontal direction, , it is found that the force of the small magnet is small when $x \leq 2$ through the analysis of the data, so $x = 2$ is taken as the dividing point in fitting.

When $x \leq 2$, the function relationship obtained by fitting the measured data with MATLAB is as follows:

$$\beta F_1(X, I_1) = -11.56 - 105.3X - 0.5329I_1$$
$$+ 152.5X^2 - 0.3639XI_1 + 0.0004411I_1^2 \quad (10)$$
$$- 83.04X^3 + 0.0211X^2I_1$$

When $2 < x \leq 6$, the function relation of fitting graph is obtained as follows:

$$\beta F_1(I_1, X) = -0.3477 + 0.1994X$$
$$- 0.0003441I_1 - 0.07086X^2 \quad (11)$$
$$- 0.000341XI_1 + 0.004748X^3$$

For the force model of the coil in the voice coil motor, because the magnetic field in the voice coil motor is evenly distributed, the magnetic field of the coil can be accurately calculated according to the magnetic circuit theorem, and then the force of the coil can be obtained through the calculation formula of Ampere force.

The specific calculation process is as follows:

The specific parameters of voice coil motor (N=100; R_{min}=10mm; R_{max}=13mm; d=10mm; B_0=0.816T) are brought into the calculation formula (4), (5), (6) to obtain $B = 0.355$T.

Therefore, the force of the coil in the voice coil motor is as follows:

$$F_2(I_2) = 2.23I_2 \quad (12)$$

According to the above-mentioned decoupling method and the function relationship obtained by fitting, the current size of the control voice coil motor (I_2)can be solved.

The following will verify the functional relationship obtained by the fitting:

For the small magnet and electromagnet models, a large number of data points are brought into the fitting function, and the size of the electromagnetic force on the small magnet is determined according to the position of the known point and the size of the current:

When the position x= 0.7mm, 1.4mm, 2.1mm, 2.8mm, and the current changes from 0mA to 1000mA.

The electromagnetic force received by the small magnet in the vertical direction and the electromagnetic force received in the horizontal direction are calculated by the fitting function, and then compared with the simulation results obtained by establishing the model in ANSYS Maxwell software. The errors obtained are shown in Table 1. :

Table 1. The force fitting error of small magnet

X/mm	Vertical force error/N	Horizontal force error/N
0.7	0.067	0.062
1.4	0.11	0.069
2.1	0.12	0.071
2.8	0.21	0.075

Through the above comparison and verification, it can be seen that the error between the simulated value and the real value is small, which can meet the control requirements of the electromagnet for the small magnet. It shows that the fitting relationship obtained by simulation can show the change of the position and current of the electromagnet and the small magnet model.

Therefore, the first step of the decoupling process can be accurately performed according to the obtained function, that is, the current magnitude of the electromagnet can be obtained by the known position and the gravity of the small magnet.

For the voice coil motor model, the second step of decoupling can be completed according to the relationship between the current and the force of the coil directly obtained by solving the formula of Abe force.

The following will verify the decoupling of the control current of the moving mirror:

Suppose the gravity of the moving mirror is 7.50 N, and the position of the moving mirror is x=1.4 mm.

It can be obtained that I_1=453.51 mA according to formula (7) and formula (9); When I_1=453.51 mA, the horizontal force of the small magnet F_1=451.19 mN from formula (10); When F_1=451.19 mN , I_2=0.202A is obtained from formula (12).

When the results are brought into the model, the vertical force F_3=7.44N and the horizontal force F_2=546.45mN.

Therefore, it can be concluded that the error between the vertical direction and the system gravity is 0.06N, which can effectively reduce the gravity of the moving mirror system; the error in the horizontal direction is 0.095N, which can be considered that the resultant force acting on the moving mirror system in the horizontal direction is 0, so the moving mirror moves uniformly in the horizontal direction.

Similarly, the position at x = 0.7mm, 1.4mm, 2.1mm, 2.8mm are selected for decoupling verification, and the decoupling methods are the same as that at x = 1.4mm. The results are shown in Table 2.

Table 2. The force of the motion mirror under the action of decoupling current control

X/mm	0.7	1.4	2.1	2.8
F_1/N	0.30	0.45	0.67	0.82
I_1/mA	451.41	453.51	462.01	476.15
I_2/A	0.13	0.20	0.29	0.37
F_2/N	0.28	0.54	0.61	0.79
Vertical resultant force/N	0.03	0.06	0.12	0.09
Horizontal resultant force/N	0.02	0.09	0.06	0.03

V. SUMMARY

By modeling the control part of the moving mirror separately, a better simulation effect was obtained. According to the modeling of different parts, the force relationship of the small magnet and the coil in their respective magnetic fields is obtained, and the reliability of the function relationship is verified through a large amount of data. With this function, we can easily decouple the control current to obtain the current that controls the voice coil motor. Through verification, the current obtained by decoupling can effectively offset the gravity of the moving mirror device in the vertical direction, and the force of the voice coil motor on the moving mirror device can offset the horizontal component force of the electromagnet on the moving mirror device in the horizontal direction. Therefore, the current obtained by decoupling can accurately control the movement of the moving mirror device, and can always maintain a constant speed and smooth movement, thereby increasing the stability and accuracy of the interferometer.

REFERENCES

[1] Liu Bo, Zhu Yong, Chen Jianjun, et al. Analysis and experiment on the tilt tolerance of a new Fourier transform spectrometer reflector[J]. Acta Photonica Sinica, 2013, 42(3): 315-319.

[2] Szymański G, Wawrzyniuk L. Effect of nonconstant mirror misalignment of moving mirror in Fourier transform spectrometer[J]. Optical Engineering, 2015,54(7):74101.

[3] Shi Lei, Liu Jia, Gao Wu, et al. Design of moving mirror system in Fourier transform infrared spectrometer[J]. Acta Photonica Sinica, 2015, 44(4): 182-187.

[4] Li Zhongbing, Xu Xianze, Le Yi, et al. Research on moving mirror motion control based on fixed lens adjustment in FTIR spectrometer[J]. Spectroscopy and Spectral Analysis, 2012, 32(8): 2295-2298.

[5] Schuerle S, Erni S, Flink M, et al. Three-Dimensional Magnetic Manipulation of Micro- and Nanostructures for Applications in Life Sciences[J]. IEEE Transactions on Magnetics, 2013,49(1):321-330.

[6] Coffin J. BEARING FOR A MOVING MIRROR OF A MICHELSON INTERFEROMETER: EP, EP 0574565 B1[P]. 1997.

[7] Ren Libing, Yang Honglei, Wei Haoyun, et al. Research on the realization of full digital control of moving mirror scanning of FTIR spectrometer[J]. Spectroscopy and Spectral Analysis, 2013, 33(8): 2263-2266.

[8] Wang Wei, Lu Yihuai, Lu Fan, et al. Design of moving mirror control system for Fourier transform infrared spectrometer based on DSP[J]. Journal of Quantum Electronics, 2015, 32(1): 8-16.

[9] Tian Yanling, Bao Yazhou, Wang Fujun, et al. Design and control of flexible positioning platform driven by voice coil motor[J]. Journal of Tianjin University: Natural Science and Engineering Technology Edition, 2017, 50(10): 1070-1076.

[10] Li Yong, Ren Liuyang, Zhang Dengping, et al. Analytical analysis and simulation of electromagnetic damping of rotating voice coil motor[J]. Micro Motors, 2016,49(6):24-27.

[11] Yin Xunfeng, Pan Songfeng, Yin Fengsong, et al. Research on the Position Control System of Linear Voice Coil Motor Based on Fuzzy PID[J]. Industrial Control Computer, 2016,29(7):16-17.

[12] Zeng Daxing, Wang Huaming, Fan Mingzhou, et al. Configuration synthesis of generalized decoupling parallel mechanism with 3 degrees of freedom rotation[J]. Chinese Journal of Mechanical Engineering, 2017,53(3):17-24.

[13] Côrtes H M, Pivoto A S D M. Modeling and Simulating of Position control of a Sphere by a magnetic levitation System on Virtual Platform[J]. 2017.

[14] Jiang Chengzhi, Liang Jingqiu, Liang Zhongyu, et al. The influence of collimation system on static Fourier transform spectrometer[J]. Spectroscopy and Spectral Analysis, 2014,34(1):274-278.

[15] Xu F, Dinavahi V, Xu X. Parallel Computation of Wrench Model for Commutated Magnetically Levitated Planar Actuator[J]. IEEE Transactions on Industrial Electronics, 2016, 63(12):7621-7631.

[16] Xiao Qianjin, Jia Hongguang, Han Xuefeng, et al. Static and dynamic performance analysis of a low-coupling movable mirror support mechanism[J]. Infrared and Laser Engineering, 2013, 42(4): 975-981.