Modern Applied Science; Vol. 8, No. 6; 2014
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Design of Voice Coil Motor for Scanning of Swinging Mirror

Rilong Liu[1]

[1] School of Engineering, Jiangxi Agricultural University, Nanchang, China

Correspondence: Rilong Liu, School of Engineering, Jiangxi Agricultural University, 1101 Zhimin Ave., Nanchang, 330045, China. Tel: 86-791-8381-3184. E-mail: ckjx312@aliyun.com

Received: July 23, 2014 Accepted: August 8, 2014 Online Published: October 19, 2014

doi:10.5539/mas.v8n6p131 URL: http://dx.doi.org/10.5539/mas.v8n6p131

The research is financed by Program for Science and Technology funded by the Education Department of Jiangxi Province (GJJ14316).

Abstract

A design method of voice coil motor is provided according to the performance of the scanning mechanism of mirror in new winging Fourier transform spectrometer. In order to meet the requirement of swinging mirror scanning technology, the movement parameters of the oscillating mechanism are presented. The voice coil motor is selected as driving motor in scanning mechanism, then the size of alnico and winding of motor is given, and the voice coil motor is designed. Finally, the performance of motor is consistent with the whole system.

Key words: voice coil motor, swinging mirror, alnico, winding, parameter calculation

1. Introduction

The scanning mirror is an important component of the new Fourier transform spectrometer. However, in order to drive the mirror to complete a swinging motion, it is necessary to take into account of the control characteristics and the driving ability in the choice of motion actuators. The stepper motor is known for its precision position control, but also for the abrupt change of its instantaneous speed, making it impossible to realize the sustained uniform motion. The synchronous motor, on the other hand, demands AC power and has a relatively slow acceleration and deceleration process, thus unsuitable for the space application of oscillating motion based on the moving mirror.

The voice coil motor is a special form of a direct dive motor with a similar working principle as the electric loudspeaker. The working principle is that in a magnetic field, the coil carrying current discharges power, the value of which is proportional to that of the coil current. To generate the rotor into reciprocating motion, the current coil should be loaded with the alternating current in the form of either the rectangular wave or the sine wave (Yeom, Park, & Jung, 2007; Moser, 1996). It should be pointed out that the voice coil motor has a structure of the moving coil type permanent magnet linear motor, mainly composed of the stator and the rotator. The stator includes a magnetic yoke and a double-bar permanent magnet of symmetrical layout, while the rotator is composed of the coil winding and the winding bracket (Zhang & Feng, 2006).

With its simple structure, small size, high speed and fast response, the voice coil motor can be sealed into a whole so that non-mechanical contact movement can be realized with minimum mechanical loss in the transmission part. These advantages make the voice coil motor the ideal choice of the driving device of moving mirrors for the majority of Fourier transform spectrometers (Ferrec, Taboury, Sauer, & Chavel, 2006; Ye, 2000). It then follows that our system adopts the voice coil motor as the mirror driving motor for the new swinging Fourier transform spectrometer. The motor herein is a moving coil linear motor capable of the specific action of the swing scanning with small amplitude. In addition, the rotator in the voice coil motor can swing the scanning platform through the connecting rod, and then drive mirrors to swing scanning.

2. Movement Parameters of Scanning for the Swinging Mirrors

To meet the requirements of the $0.625cm^{-1}$ high spectral resolution task, the Fourier transform spectrometer needs an optical path difference above 1.6cm. According to the design requirements of the interferometer, the angular velocity of the swing mirror uniform section is $\omega = 0.533 rad / s$ (Hu, 2008).

Because the system uses the voice coil motor to drive the interference mechanism of swing scanning, the linear motion has to be converted to the swing motion. It is feasible to link the motor and the swing scanning mechanism by means of the connecting rod. In this way, the movement parameters of the swing scanning mechanism calculation will assume more flexibility, because changes in the length of the connecting rod can directly lead to the variation in the voice coil motor force constants. If the connecting rod length is the distance between the motor rotor and the gyration center in the swing scanning mechanism, its value is 20cm and the torque equation is

$$FL = I\frac{d\omega}{dt} \quad (1)$$

The moving mirror and other necessary mechanical supports make up the load of the voice coil motor. If the load weight is 3kg, then the moment of inertia I is 0.05 kgm^2. If the swing arm is 20cm, the swing angle β is 6°, and the swing period is 0.5s, we can get the voice coil motor continuous thrust:

$$F = \frac{I}{L}\frac{d\omega}{dt} = \frac{0.05}{0.2}\cdot\frac{0.533}{0.025} = 5.33N \quad (2)$$

Then the trip of voice coil motor is:

$$x_m = 20\times 6^\circ = 2.09cm \quad (3)$$

3. Calculation and Analysis of the Alnico

3.1 Performance Comparison of Permanent Magnetic Materials

There are many types of permanent magnetic materials, and the commonly used permanent magnetic materials usually refer to ferrite, AlNiCo, MnAlN and rare earth permanent magnetic materials. The rare earth cobalt permanent magnet and Neodymium iron boron (NdFeB) permanent magnet are rare earth permanent magnetic materials of different categories. It should be pointed out that NdFeB permanent magnetic materials, for its excellent magnetic properties, have been chosen to replace the original permanent magnetic material by power motor and micro motors both home and abroad (Zhong, 1998). Table 1 compares the magnetic properties between NdFeB permanent magnetic material and other permanent magnet materials

Table 1. Comparison of magnetic properties

Permanent magnetic material	B_r (T)	H_c (kA/m)	$(BH)_{max}$ (kJ/m^3)
ferrite	0.385	235	28
AlNiCo	1.230	51	44
MnAlN	0.560	239	61
$SmCo_5$	0.870	637	146
NdFeB	1.230	881	290

As is shown in Table 1, for the NdFeB permanent magnetic material, the residual magnetic induction intensity B_r, the coercivity of magnetic flux H_c and the maximum energy product $(BH)_{max}$ are greater than those of the other permanent magnet materials. All this attests the fact that NdFeB, for the best performance of permanent magnetic materials, has been widely used in permanent magnet motors.

In the manufacture cost of the voice coil motor, the ferrite motor magnet has the minimum manufacture cost, followed by NdFeB, AlNiCo and rare earth cobalt. For the permanent magnet of low magnetic energy, reduction of electrical and magnetic materials can greatly lower the cost of the motor. Meanwhile for the permanent magnet of high magnetic energy, the magnet should decrease in order to cut down the cost of the motor.

Under the circumstance of equal output thrust in the voice coil motor, the NdFeB permanent magnet is found to have the minimum size and weight. This is because the NdFeB permanent magnet is of high magnetic energy, thereby able to produce the air gap of higher flux and the magnetic load, and diminishing the size of the permanent magnetic material. Therefore, considering the voice coil motor size and the manufacturing cost, the NdFeB permanent magnet is selected as the alnico of motor for driving the interference mechanism.

3.2 Design of the Permanent Magnet in Motor Magnetic Circuit

As the magnetic source component, the permanent magnet should meet the following requirements in the motor magnetic circuit. First, its size and performance both need to satisfy the requirements of air gap flux. Next, it should meet the demands of the flux stability, wherein the influence of temperature and time should not exceed the allowable range on the magnetic flux.

Given the magnetic flux leakage and magnetic potential drop in the motor magnetic circuit, we get two basic equations of the magnetic circuit design (Zhong, 1998; Luo & Zhang, 1999)

$$\begin{aligned} \Phi &= B_m A_m = k_f B_g A_g \\ F &= H_m L_m = k_r H_g L_g \end{aligned} \quad (4)$$

where k_f is the magnetic flux leakage coefficient;

k_r is the magnetic reluctance coefficient;

B_m and H_m are the working points of the permanent magnet;

A_m, L_m are the area and thickness of the permanent magnet, respectively;

B_g, H_g, A_g and L_g are the air gap flux density, the magnetic field intensity, the air gap size and the gap length.

From Eq. (4), we get the following equation:

$$B_g^{\ 2} = B_m H_m \frac{V_m}{V_g} \frac{u_0}{k_f k_r} \quad (5)$$

Where, $B_m H_m$ is the magnetic energy product of the permanent magnet's working point. The definitions of V_m and V_g are:

$$\begin{aligned} V_m &= A_m L_m \\ V_g &= A_g L_g \end{aligned} \quad (6)$$

Where, V_m represents the permanent magnet size, and V_g stands for the air gap size. If the working point is the maximum magnetic energy of the material, then Eq. (6) shows that the minimum size of the permanent magnet is required when the air gap flux density and the air gap size reach the same request.

Given the known air gap parameters B_g, A_g, L_g and the permanent magnet operating point, the magnetic flux leakage coefficient k_f and the magnetic reluctance coefficient k_r are the two prerequisites for the calculation of the permanent magnet dimension. The value of k_r allows slight changes generally between 1.05 to 1.45, whereas the value of k_f may vary greatly in different magnetic circuit structures (Luo & Zhang, 1999).

If the performance parameters are considered and the alnico is the NTP240SH NdFeB permanent magnetic material, the demagnetization curve of the NdFeB permanent magnetic material is shown in Figure 1 (Wei, 2010; Chinese Standardization Management Committee, 2009):

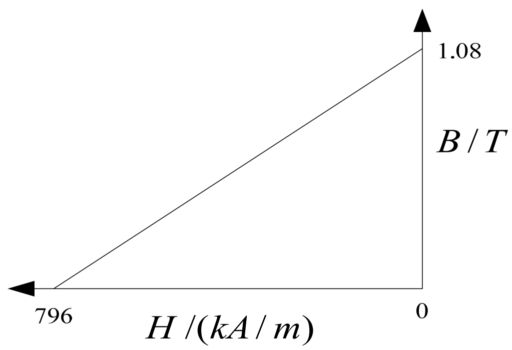

Figure 1. The demagnetization curve of the NTP240SH NdFeB

When the magnetic flux density of the working point is $B_m = 0.81T$, then we get the field intensity $H_m = 198kA/m$. If the permanent magnet remanence is $B_r \geq 1.08T$, then we get the coercivity of magnetic flux $H_c \geq 796kA/m$.

In order to obtain the magnetic flux leakage coefficient k_f, the magnetic circuit can be converted into the equivalent electric circuit through the method of magnetic conductance. Calculations are then made for the various sections in the magnetic conductance (Zhong, 1998; Chen, Fuh, & Tung, 2005). The air-gap permeance P_g between the rectangular poles is:

$$\frac{P_g}{\mu_0} = \frac{A_g}{L_g} = \frac{4\times 2}{0.3} = 26.67 \quad (7)$$

The permeance P_1 on the surface between the rectangular poles is:

$$\frac{P_1}{\mu_0} = \frac{a}{\pi}\ln(1+\frac{2b}{L_g}) = \frac{4}{\pi}\ln(1+\frac{2\times 2}{0.3}) = 3.39 \quad (8)$$

The permeance P_2 between the magnetic end angles is:

$$\frac{P_2}{\mu_0} = 0.077L_g = 0.077\times 0.3 = 0.02 \quad (9)$$

Then we get the total permeance P as follows:

$$\frac{P}{\mu_0} = (\frac{P_g}{2} + 2P_1 + 2P_2)\frac{1}{\mu_0} = \frac{26.67}{2} + 2\times 3.39 + 2\times 0.02 = 20.16 \quad (10)$$

Therefore, the magnetic flux leakage coefficient is:

$$k_f = \frac{P}{P_g/2} = \frac{20.16}{13.34} = 1.51 \quad (11)$$

If the reluctance coefficient $k_r = 1.2$, then the air gap flux density is $B_g = 0.65T$, and the air gap length is $L_g = 0.3cm$ in accordance with the voice coil motor design requirements. When these values are substituted to Eq. (4), we can get the NdFeB permanent magnet thickness:

$$L_m = \frac{k_r B_g L_g}{\mu_0 H_m} = \frac{1.2\times 0.65\times 0.3}{4\pi\times 10^{-7}\times 198\times 10^3} = 0.95cm \quad (12)$$

And the permanent magnet area is:

$$A_m = \frac{k_f B_g A_g}{B_m} = \frac{1.51\times 0.65\times 4\times 2}{0.81} = 9.69cm^2 \quad (13)$$

Eq. (3) has already given the trip of voice coil motor $x_m = 2.09cm$. Then combining the calculated valued in Eq. (13) and Eq. (14) with the motor structure and the motion length of the moving coil, we can decide on the permanent magnet size: length 4.5cm, width 2.2cm. In this way, we can finally obtain the volume of the NdFeB permanent magnet material $4.5cm\times 2.2cm\times 0.95cm$, which well fits the design requirements of the magnet of the voice coil motor.

4. Calculation and Design of the Coil

Based on the already-known parameters of the mirror scanning movement, we get the motor thrust $F = 5.33N$. In light of the principle of the ampere force, we get:

$$F = B_g L_c I \quad (14)$$

where B_g is the air gap flux density;

L_c is the effective length of the coil conductor in the magnetic field;

I is the current in the coil conductor.

Then we get:

$$I = \frac{V}{R}$$
$$L_c = \gamma L_t \quad (15)$$
$$R = \frac{\rho L_t}{S}$$

where L_t is the length of the coil wire;

γ is the proportional coefficient;

ρ is the resistivity of copper wire;

S is the cross-sectional area of conductor.

Then Eq. (14) can be rewritten as follows:

$$F = \frac{B_g \gamma V S}{\rho} \quad (16)$$

From Eq. (16), we can get the wire cross section area:

$$S = \frac{F\rho}{B_g \gamma V} = \frac{5.33 \times 1.74 \times 10^{-8}}{0.65 \times 0.17 \times 5} = 0.168 \times 10^{-6} m^2 \quad (17)$$

Then the wire diameter is:

$$d = \sqrt{\frac{4S}{\pi}} = \sqrt{\frac{4 \times 0.168 \times 10^{-6}}{3.14}} = 0.462mm \quad (18)$$

According to the specification of enamelled round copper wire, we can decide on the diameter of copper wire $d = 0.470mm$, the wire area $S = 0.1735mm^2$, and the corresponding thin enamel insulated wire's maximum diameter $0.510mm$ (Wei, 2010). It should be made clear that the enamelled wire is wound into 4 layers, with each layer of 80 turns and altogether 320 turns in the motor coil.

It is stipulated in the design reference that the voice coil motor rated current is of 0.5~1A. Then based on Eq. (11) and Eq. (12), we get the coil wire length:

$$L_t = \frac{L_c}{\gamma} = \frac{F}{B_g I \gamma} = \frac{5.33}{0.65 \times 1 \times 0.17} = 48.2m \quad (19)$$

Applying the above value to Eq. (15), we get the wire resistance expressed as:

$$R = \frac{\rho L_t}{S} = \frac{1.74 \times 10^{-8} \times 48.2}{\pi \times 0.235^2 \times 10^{-6}} = 4.83\Omega \quad (20)$$

Since the current value is determined by the power drive circuit in the voice coil motor, the 5V voltage across the load coil leads to:

$$I = \frac{V}{R} = \frac{5}{4.83} = 1.03A \quad (21)$$

Meanwhile the corresponding electromagnetic thrust is:

$$F = B_g L_c I = 0.65 \times 0.17 \times 48.2 \times 1.03 = 5.49N \quad (22)$$

Eq. (22) manifests clearly that the theoretical calculation value of the coil satisfy the design requirements of the voice coil motor.

In order to make more effective use of the air gap in the process of coil winding, the coil mass should be reduced and direct winding should be adopted instead of inserting traditional insulation winding films between each layer winding. The quick drying glue can be used to stick together the enameled wires to ensure the firmness and the overall rigidity of the coil.

5. Conclusions

In accordance with the technology of the swinging mirror scanning, we can determine the movement parameters of the swing mechanism. After choosing the voice coil motor as the driving motor, we should further take the motor size and the manufacturing cost into account, and adopt the NTP240SH NdFeB permanent magnet as the magnet steel in the voice coil motor with the insulated wire of the diameter 0.510mm .

With more calculations and analyses on the motor alnico and coil, we successfully designed the voice coil motor capable of swinging mirror scanning, which well meets the requirements of the overall system.

References

Chen, Y. D., Fuh, C. C., & Tung, P. C. (2005) Application of voice coil motors in active Dynamics vibration absorbers. *IEEE Transactions on Magnetics*, *41*(3), 1149-1154. http://dx.doi.org/10.1109/TMAG.2004.843329

Chinese Standardization Management Committee. (2009). *Materials for Sintered NdFeB permanent magnets*. Beijing: Chinese Standardization Management Committee.

Ferrec, Y., Taboury, J., Sauer, H., & Chavel, P. H. (2006). Optimal geometry for Sagnac and Michelson interferometers used as spectral imagers. *Optical Engineering*, *45*(11), 1156011-1156016. http://dx.doi.org/10.1117/1.2395923

Hu Y. (2008). *Research on the driving system of moving mirrors in Fourier transform spectrometer* (Unpublished master's thesis). Chinese Academy of Sciences, Shanghai, China.

Luo, G., & Zhang, B. (1999). Design of servo pattern voice coil motor for optical pre-etching machine. *Micro motor*, *27*(2), 19-22.

Moser, M. A. (1996). Shorted turn effects in rotary voice coil actuators. *IEEE Transactions on Magnetics*, *32*(3), 1736-1742. http://dx.doi.org/10.1109/20.492858

Wei, J. W. (2010). *Small power permanent magnet motor principle, design and applications*. Beijing: Machinery Industry Press.

Ye, Y. Y. (2000). *Principle and application of linear motor*. Beijing: Machinery Industry Press.

Yeom, D. H., Park, N. J., & Jung, S. Y. (2007). Digital controller of novel voice coil motor actuator for optical image stabilizer. *IEEE International Conference on Control, Automation and Systems*, 2201-2206. http://dx.doi.org/10.1109/ICCAS.2007.4406698

Zhang, D. W., & Feng, X. M. (2006). Technical principle of the voice coil motor. *Journal of North University of China*, *27*(3), 224-228.

Zhong, W. D. (1998). *The ferromagnetism*. Beijing: Science Press.

Copyrights