The Twelfth International Symposium on Magnetic Bearings (ISMB 12)
Wuhan, China, August 22-25, 2010

Design and Optimization of Axial Position Sensing System in Maglev Blood Pump

Zhang Yunpeng[1,a], Liu Shuqin[1,b], Guan Yong[1,c], Fan Youpeng[1,d]
[1] School of Electrical Engineering, Shandong University, Jinan, 250014, China
[a]zhangyp@sdu.edu.cn, [b]lshuqin@sdu.edu.cn, [c]yongguan@sdu.edu.cn, [d]fightingfyp@163.com

Abstract: The position sensing system is one of the most important parts in maglev artificial heart pump. This paper describes a newly developed axial position sensor system. The position sensing system is designed to be combined with the radial permanent magnetic bearing and used for the control of the axial active magnetic bearing. The rotor ring of the radial magnetic bearing is used as field source, which shortens the rotor and saves space for maglev blood pump design. Linear hall sensor is selected due to its low cost and miniature size. The principle of the position sensing system is based on the analysis of the magnetic field of the permanent magnetic bearing and the sensor module is designed via finite-element analysis to optimize sensitivity and accuracy of the measured signals. An applied primary amplifier circuit for the position sensing is designed and its performance is tested. The experimental results demonstrate that the position sensing system has a satisfactory performance and is effective for axial control.

Keywords: Maglev Blood Pump, Permanent Magnetic Bearing, Hall Sensor, Position Sensing

[1] Introduction

Studies have shown that failure of the cardiovascular system is one of the most common health disorders causing premature death in our society. For supporting the blood circulation of heart failure patients, various kinds of artificial heart pumps (blood pumps) have been developed and used at the clinical stage. Beyond second-generation blood pump, third-generation blood pump is mechanical noncontact by utilizing magnetic suspension mechanisms. Since magnetic levitation will eliminate mechanical contact, which leads to material wear, red blood cell damage, heat generation, platelet aggregation, thrombus growth and even pump failure, maglev blood pumps have widely potential applications[1-2].

The position sensing system is one of the most important parts in magnetic levitation system of maglev blood pump since it is necessary to the active controlling. The accuracy of the sensing system determines the performance and security of the maglev blood pump. Common contactless linear position sensing devices used in industry include capacitive, inductive, hall-effect, magneto-resistive, optical, and ultrasonic, etc[3-7]. Usually, eddy current sensors are used in magnetic bearings (MBs) for position measurement due to their accuracy and non-contact nature. However, these sensors are expensive and bulky for implementation in small maglev drives such as maglev blood pump. Hall sensors are preferred since they are small in size, reliable, robust, and low-lost. Furthermore, hall sensor can be covered by nonmagnetic biocompatible material such as medical titanium alloy, which is between the hall sensor and the field source and solves the biocompatible problems. It is difficult for other sensors to solve similar biocompatible problems. But, the known hall-effect based linear position sensors are limited in accuracy by offset, temperature dependence, and ageing. Another drawback of these devices is the strong non-linear decrease of the magnetic field strength with distance from the field source, unless the sensor system is particularly designed. In general, it is necessary to compensate for these shortcomings in position sensing design, calibration and digital signal processing. Sheng-Ming Yang et al. presented a sensing system based on Hall sensor in maglev blood pump, in which an additive ring shape permanent magnet is mounted on the rotor as the magnetic field source [6]. Kun-xi Qian et al. measured the position of rotor in centrifuge blood pump by using Hall sensor, but the signal is not processed and used for active controlling [2].

In this paper, a new position sensing system combined with the radial permanent MB is proposed and its signal is used for the control of the axial active MB in maglev blood pump. The rotor ring of the radial MB is used as field source, which shortens the rotor and saves space for blood pump design. Based on the analysis of the magnetic field of the permanent MB, the position of hall sensor and its azimuth angle were optimized for high sensitivity and accuracy. An applied primary amplifier circuit for the position sensing is designed and its performance is tested. The prototype test results indicate that this position measurement system has a good output performance and satisfied the axial active controlling. Moreover the length of the rotator is decreased and the structure of blood pump is simplified by using this position sensing system.

[2] Magnetic bearing and sensing system

The structure of our maglev blood pump is shown in Fig. 1. The pump includes straightener, impeller, diffuser, motor, permanent MBs, axial MB, rotor and housing. The magnetic levitation system consists of two radial permanent MBs and one axial active MB. Each permanent MB has two inner and two outer rings shaped permanent magnet. The inner rings are mounted on the rotor, and the outer rings are bonded to the inner surface of the stator. The rotor radial direction is stabilized by using permanent MB passively. The rotor axial direction is controlled using an active electromagnetic MB. The position sensing system is combined with the radial permanent MB and provides the axial position signal for axial active controlling.

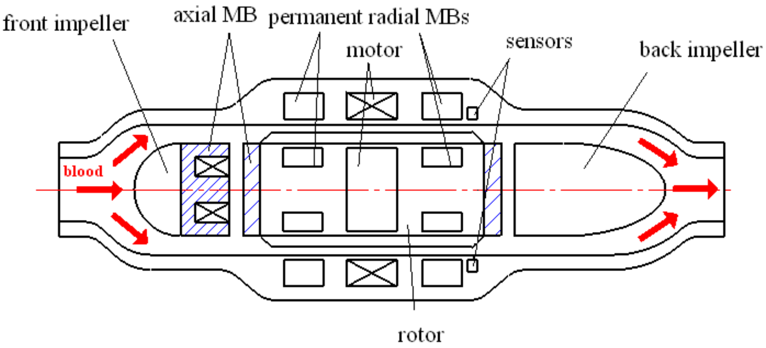


Fig. 1 Cross-sectional view of the blood pump

Because of the axial-flow pump structure, it is inconvenient to install a rotor axial position sensor directly in the flow path due to the outlet wires and sealing problems. In our design, four commercially available linear hall-effect sensors positioned on the inner stator surface near the permanent MB are utilized to measure the axial displacement. The rotor ring of the radial MB is used as field source for shortening the rotor and saving space. These sensors are placed close to the stator ring of radial permanent MB and detect magnetic field variations caused by rotor ring movement, which avoids the contract with the blood. A schematic of the sensor arrangement is shown in Fig. 2.

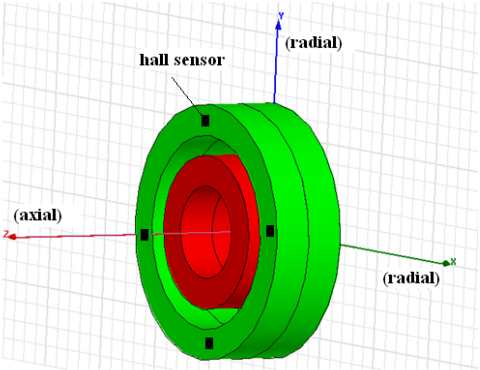


Fig. 2 Schematic of the sensor arrangement with radial permanent MB

Hall sensors are non-contact position measurement devices. When magnetic field affects on the device, a voltage which is proportional to the flux density is induced at the output. Commercially available linear hall sensors are used in the proposed measurement system. The operating range of these devices is ±900 Gauss, and the corresponding output voltage is 0 to 5 V. Commonly the hall sensors prefer to be fixed close to the magnetic field source since the intensity of field is proportional to $1/r^2$ where r is the distance between the hall sensor and field source. In our design, the magnetic field of stator ring magnet of permanent MB will affect the hall sensor more than that of rotor ring magnet. It may saturate the hall sensors since the magnetic field is about 1T at NbFeB magnet surface. So it is necessary to investigate the characters of magnetic field and determine relative position of hall sensors in the system. In the following, the magnetic field distribution of permanent MB is analyzed and the position of hall sensor and its azimuth angle were optimized for high sensitivity and accuracy.

[3] Magnetic field analysis of the permanent magnetic bearing

In order to measure position of the levitated rotor, the magnetic field of the rotor ring of radial permanent MB is selected as field source and measured by the hall sensors. The magnetic field of axial permanent MB can be obtained according to the analytical 3-D formulation. R. Ravaud et al. presented the analytical formulations of the magnetic field created by permanent-magnet rings based on the coulomb model[8]. The results obtained by a 2-D analytical approximation and those obtained by the 3-D analytical formulation are compared and it is showed that 3-D analytical formulation is more accurate in conditions with large distance of the observation point from the magnet and small radius of the magnet. In the maglev blood pump, the hall sensors are placed outside the blood house and the radius of rotor ring magnet is minimized for space saving. Therefore the magnetic field of ring magnet is calculated according to 3-D analytical formulation in this paper.

The geometry considered and the related parameters in the model are shown in Fig. 3. The ring inner radius is r_{in}, the ring outer radius is r_{out}, and its height is h. The axis is an axis of symmetry. Calculations are obtained by using the Coulomb model. Consequently, the permanent magnet ring is represented by two annular planes which correspond to the upper and lower faces of the ring. The upper one is charged with a surface magnetic pole density σ^*; the lower one is charged with the opposite surface magnetic pole density $-\sigma^*$, which is determined by the properties of permanent magnetic material.

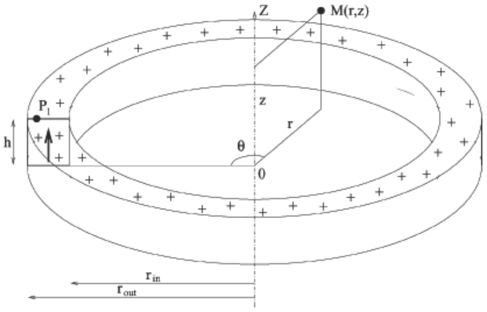


Fig. 3 Schematic of coulomb model of permanent magnet ring [8]

The magnetic field created by the ring upper face at observation point (r,z) of the space is given by[8]:

$$\vec{H}(r,z)=\frac{\sigma^*}{4\pi\mu_0}\int_{\theta=0}^{\theta=2\pi}\int_{r_1=r_{in}}^{r_1=r_{out}}\frac{\overline{P_1M}}{\left|\overline{P_1M}\right|^3}r_1dr_1d\theta \tag{1}$$

The integration of (1) leads to the magnetic field components along the three defined axes: $H_r(r,z)$, $H_z(r,z)$, $H_\theta(r,z)$,which are given by the expressions (3), (4), and (9) in the references[8]. And the magnetic magnetic flux density $B(r,z)$ is expressed as following:

$$B(r,z)=\mu_0 H(r,z) \tag{2}$$

The following are the dimensions of the PM bearings in Fig.3:

1) stator rings: r_{out}=16.6mm, r_{in}=12.6mm, and h=5 mm;

2) rotor rings: r_{out}=10mm, r_{in}=6mm, and h= 5 mm.

Fig. 4 shows the Radial magnetic field distribution of rotor ring in axial direction calculated by analytical 3-D formulation, which is used for optimizing of sensing system in the following. In this paper, analytical 3-D formulation and finite elements method (FEM) were both used for magnetic field calculation.

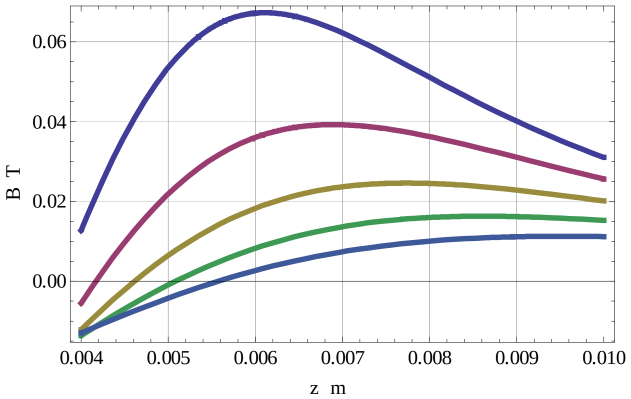


Fig. 4 Radial magnetic field distribution of rotor ring in axial direction calculated by analytical 3-D formulation.

[4] Optimizing of the sensing system

A. *azimuth angle of hall sensors*

Hall sensor is design to detect the magnitude of magnetic field perpendicular to the measurement plane, which can be expressed as [9]:

$$U_H=K_H IB_n \tag{3}$$

where U_H is the output voltage of hall sensor, K_H is hall constant, I is current, $B_n=B\cos\theta$ is vertical component of magnetic field, θ is the angle between magnetic field and normal to the measurement plane.

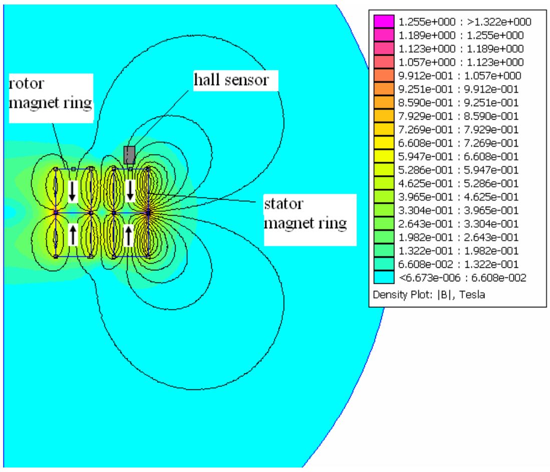


Fig. 5 Magnetic flux and magnetic field distribution of radial permanent MB

In our design, for convenience the hall sensors can be placed axial or radial to measure the radial or axial components of magnetic field. Fig. 5 shows the magnetic flux and magnetic field distribution of radial permanent MB. Fig. 6(a) and (b) show the magnetic field distribution of stator ring in axial direction calculated by FEM. Different curves (r=12.6mm~16.6mm) represent the different radial position of hall sensors, respectively. The axial magnetic field of stator ring magnet B_{1Z} is above 0.1T in the region of z<3mm and 13.6mm<r<15.6mm, which will saturate the hall sensors. And B_{1Z} in r=12.6mm, 15.6mm and z<3mm is larger than 0.5T, which is near to the saturation magnetic field. Despite of orientation of magnetic field, the radial magnetic field of stator ring magnet B1R decreases with increasing z position. Therefore, the hall sensors should be fixed at r=13.6-15.6mm and measurement plane should be parallel to the axial axis for measuring the radial component of magnetic field.

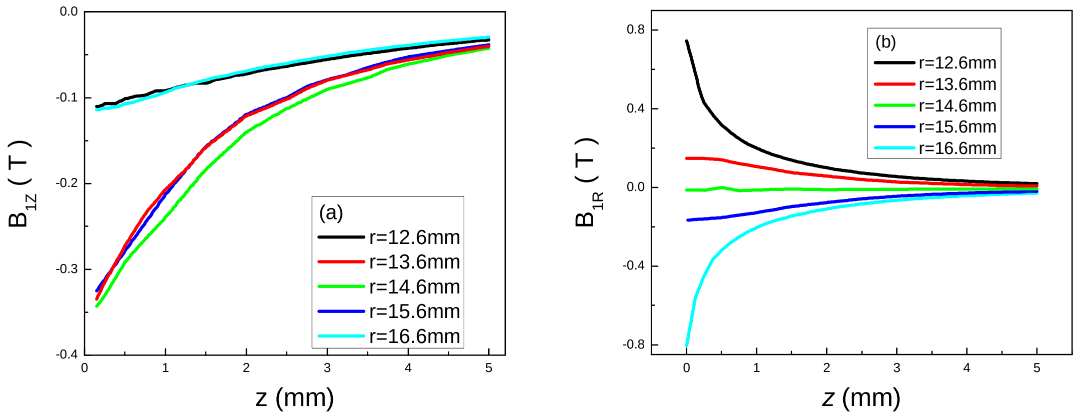


Fig.6 Axial (a) and radial (b) magnetic field distribution of stator ring in axial direction calculated by FEM

B. radial and axial position of hall sensors

In order to optimizing the axial position of hall sensors, radial component of magnetic field of rotor ring magnet B_{2R} is calculated and shown in Fig. 7 by FEM. It is accordance to the calculated results by analytical 3-D formulation which is shown in Fig. 4. It can be seen that the B_{2R} increases in -1mm<z<1mm region and then decreases with increasing z displacement. Moreover, B_{2R} decreases with decreasing the distance between hall sensors and rotor ring magnet which consists with the Biot-Savart law. For high sensitivity and accuracy the hall sensors should be fixed in the region of r=13.6mm and -1mm<z<1mm.

In actual design used in the prototype pump the position of hall sensors is r=13.6mm and z=0.3mm.

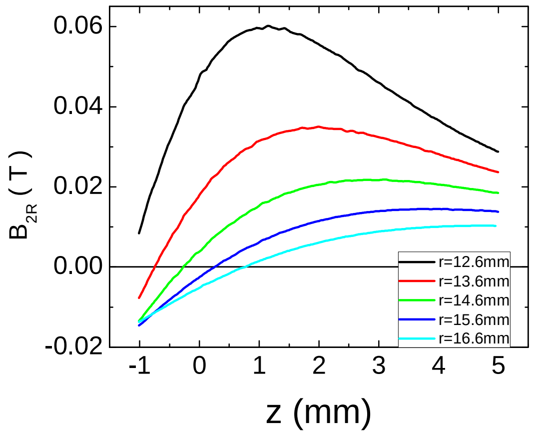


Fig.7 Radial magnetic field distribution of rotor ring in axial direction by FEM

[5] Signal processing

In above design, the output of hall sensors presents the change of magnetic field which is caused by not only axial movement but also radial movement. In order to eliminate the effect of radial displacement on axial position measurement, two hall sensors are placed on radial center of symmetry. The relationship between hall sensors output and rotor radial displacement can approximated to be linear, because that the radial space gap is smaller than 0.15mm. By adding the output value by two hall sensors output, the rotor radial displacement may be eliminated in the axial position measurement. When the rotor has axial displacement Δz and radial displacement Δr, the hall sensors output can be express as:

$$U_1 = U_0 + K_z \cdot \Delta z + K_R \cdot \Delta r, \qquad (4)$$
$$U_2 = U_0 + K_z \cdot \Delta z - K_R \cdot \Delta r.$$

where K_z and K_R are the axial and radial hall constants respectively. Thereby the output by adding those of two hall sensors is:

$$U_{out} = (U_1 + U_2) = 2K_z \cdot \Delta z \qquad (5)$$

Actually in the prototype, there are four hall sensors squarely fixed in the radial direction, which will also reduce the magnetic inhomogeneity effects on the position measurement.

In order to reduce the noise of hall sensors, it is a common method to reduce the signal bandwidth, which can be achieved by using active filter. In our design, the bandwidth of hall sensor is 23kHz and the frequency used is below 150Hz due to the maximum rotating speed

9000rpm. Therefore active low-pass filter with cut-off frequency 1500Hz is used for reduction of high-frequency signal wave interference. At the same time, integrated filter circuit operational amplifier provides high input resistance and reduces influence of changing of hall sensor resistance on the circuit state. The flowchart for the signal processing is shown in Fig.8.

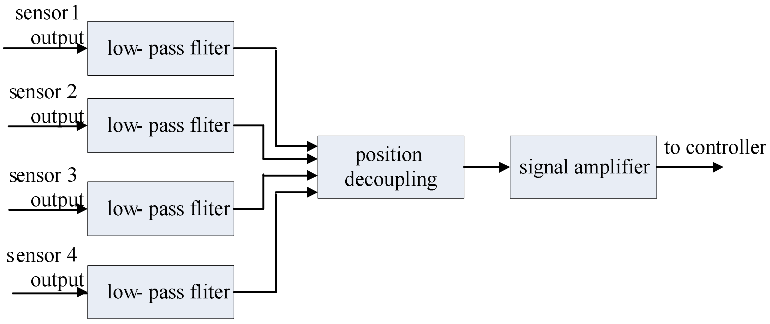


Fig. 8 Flowchart for the signal processing.

The decoupled position signals are amplified by signal amplifier for axial active controlling. For high stability and reliability of the circuit, three op-amp integrated amplifier circuit based on AD620 is used for signal amplifying. The AD620 IC is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1 to 10,000. Furthermore, the AD620 features 8-lead SOIC and DIP packaging that is smaller than discrete designs and offers lower power (only 1.3 mA max supply current), making it a good fit for battery-powered, portable (or remote) applications.

[6] Experimental results

An experimental system was setup to verify the proposed measurement system. The system consisted of permanent MB, position sensing system and a mechanical dial gauge. Rotor position in axial directions can be adjusted. A motor attached at one end of the rotor provided rotational torque. For comparisons, a mechanical dial gauge was used to measure the actual rotor position in axial direction. The sensor output voltages were measured. The picture of the radial permanent MB combined with hall sensors is shown in Fig.9.

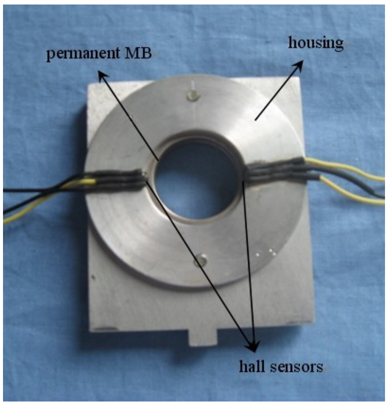


Fig.9 Picture of permanent MB and hall sensors

Fig.10 shows the axial positions measured by the sensor system vs. the positions measured by mechanical dial gauge when the rotor was not rotating. Horizontal axis is the position measured by mechanical dial gauge, and vertical axis is the position measured by the hall sensors. It can be seen that there are coupling between the axial and the radial positions since that the curves measured from single hall sensor are not linear. The results shows that the position signal output by adding two hall sensors is almost linear and consistent to the actual magnitude. Thereby the proposed position measurement design eliminates the effect of radial displacement on the axial position measurement.

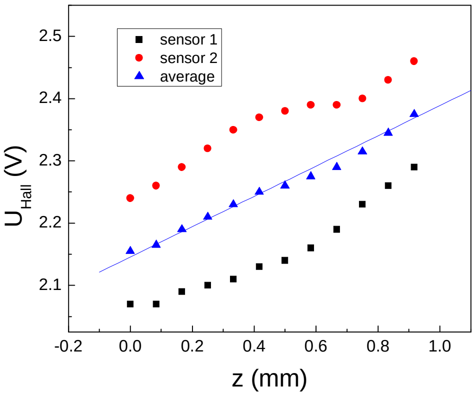
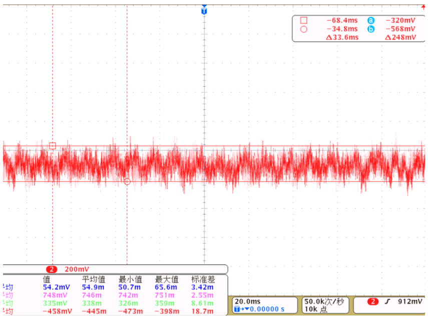


Fig.10 Experimental results of axial position measurement

Fig. 11 shows the measured rotor position when the rotor is levitated. The rotor position was calibrated. It can be seen that noticeable oscillations existed in the radial directions which origins from the axial PID controlling. Moreover the axial position of rotor is controlled in a range of 0.01mm. The experimental results proved that the position sensing system has a satisfactory performance and is effective for axial control.



	值	平均值	最小值	最大值	标准差
均	54.2mV	54.9m	50.7m	65.6m	3.42m
均	748mV	746m	742m	751m	2.55m
均	335mV	338m	326m	359m	8.61m
均	−458mV	−445m	−473m	−398m	18.7m

Fig. 11 Rotor axial position when the rotor was levitated in air

Summary

A sensor system based on hall-effect sensors to measure axial position of a magnetically levitated rotor of blood pump was presented in this paper. The position sensing system is designed to be combined with the radial permanent magnetic bearing and used for the control of the axial active magnetic bearing. The rotor ring of the radial magnetic bearing is used as field source, which shortens the rotor and saves space for blood pump design. The position of hall sensor was optimized according to the analysis of the magnetic field. An applied primary amplifier circuit for the position sensing is designed and its performance is tested. The experimental results demonstrate that the position sensing system has a satisfactory performance and is effective for axial control.

References

[1] Hideo Hoshi, Tadahiko Shinshi,and Setsuo Takatani. “Third-generation Blood Pumps With Mechanical Noncontact Magnetic Bearings”. Artificial Organs, vol. 30, pp. 324–338, 2006.
[2] K.X. Qian, P. Zeng, W.M. Ru, H.Y. Yuan. “New concepts and new design of permanent maglev rotary artificial heart blood pumps.” Medical Engineering & Physics, vol. 28, pp. 383–388, 2006.
[3] ZOU Hai-dan，ZHU Huang-qiu. “Summary of Displacement Detection Technique for Magnetic Bearings.” Bearing, vol. 4, pp. 53-56, 2006.
[4] Goldowsky, Michael P. “Magnetic suspension blood pump.” United States Patent 6716157, 2004.
[5] Wampler, Richard K, Lancisi, David M. “Active magnetic bearing system for blood pump.” United States Patent 6264635, 2001.
[6] Sheng-Ming Yang, Chun-Cheng Lin. “Performance of a Single-Axis Controlled Magnetic Bearing for Axial Blood Pump.” Industry Applications Conference, 2007. 42nd IAS Annual Meeting. Conference Record of the 2007 IEEE. pp.963-968, 2007.
[7] WAN Fu-kai，RU Wei-min，ZENG Pei，YUAN Hai-yu，QIAN Kun-xi. “Rotor position measurement of permanent maglev heart pump by use of Hall sensors.” Journal of Jiangsu University(Natural Science Edition), vol. 25, pp. 64-67, 2004.
[8] R. Ravaud, G. Lemarquand, V. Lemarquand, C. Depollier. “Analytical Calculation of the Magnetic Field Created by Permanent-Magnet Rings”. IEEE Transactions on Magnetics, vol. 44, pp.1982-1989.
[9] ZHAO Kaihua，CHEN Ximou. Electromagnetic. Higher Education Press，1985.