Design and Electromagnetic Analysis of a Superconducting Diamagnetic Motor

Muxi Shang, Yinming Dai, Qiuliang Wang, Yunjia Yu, Baozhi Zhao, Keeman Kim, and Sangjun Oh

***Abstract*—A diamagnetic motor based on Meissner effect of low temperature superconductor (LTSC) in ultra low temperature has been studied. In this new superconducting motor, the stator is in the center of the rotor and the rotor is driven by the diamagnetic force. The principles and the different designs of this kind of motor are described in the paper. The analysis of electromagnetic configuration on a two-phase system design is carried out and the detailed data of the driving torquers of the motor are presented.**

***Index Terms*—Electromagnetic configuration, LTSC superconducting motor, Meissner effect.**

I. Introduction

SOME instruments need accurate and steady motor, however, frictional forces are a barrier to many motors applied in this field. The friction has much influence on accuracy and stability of the motor. Levitating rotors then were proposed to avoid the friction.

In this paper the design and analysis of a new accurate and steady superconducting motor is presented. This motor is manufactured with high purity niobium and the stator is in the center of the rotor. The rotor is levitated and driven by the diamagnetic force applied on the surface of the niobium. The motor must be run at the temperature below 4.2 K.

The levitating and driving principles are briefly reviewed, the design and fabrication and also the electromagnetic analysis on the motor are described as well.

II. Working Principle

It is well known that according to so-called Meissner effect, at a operating temperature below the critical temperature T_c, a pure superconductor will not allow any magnetic field to freely enter it. This implies that if a magnet is placed on the top of the superconductor when the superconductor was cooled down below T_c, the superconductor would then exclude the magnetic field of the magnet. This phenomena can be seen quite clearly since the magnet is repelled and levitated above the superconductor. It must be attention that the phenomena will occur only if the strength of the applied magnetic field does not exceed the value of the critical magnetic field H_c for the superconductor material.

Manuscript received September 9, 2005. This work was supported in part by the National Science Foundation of China with Contract and High Technology Program of China 863.

M. Shang, Y. Dai, Q. Wang, Y. Yu, and B. Zhao are with the Institute of Electrical Engineering, Beijing 100080, China (e-mail: smx@mail.iee.ac.cn; qiuliang@mail.iee.ac.cn).

K. Kim and S. Oh are with the Korea Basic Science Institute, Taejon 305-333, Korea (e-mail: kkeeman@kbsi.re.kr).

Digital Object Identifier 10.1109/TASC.2005.869686

Based on the theory of electromagnetic and the phenomena of Meissner effect, if a superconductor is moved into a magnetic field, there will be an induced current in the surface of the superconductor according to Faraday Induction Law, the thickness of the surface is of the order of 10^{-4} mm [1]. The magnetic field associated with the induced current would oppose the applied field the superconductor appears perfectly diamagnetic, and there will be a force between the superconductor and the magnet, then the noncontact levitating superconducting motor by using this diamagnetic force can be achieved.

High purity niobium was chosen because of its relatively high critical field and critical temperature.

According to the current flows in the surface of superconductor, the following formula can be deduced:

$$F = \frac{\Delta l \Delta a}{2\mu_0} B_0^2 \quad \frac{N}{m^2}. \tag{1}$$

This formula can calculate the intensity of pressure caused by diamagnetic force [2]. In this formula, Δl and Δa are the encircled length and width of induced current respectively. Of course, it should be mentioned that H_0 (corresponding to B_0) has to be lower than the critical field (H_{C1}). In 1987, A. Rivetti discovered that the flux intensity of pressure on the surface of niobium must be lower than 30 kPa $(3\ \mathrm{N/cm^2})$ before the applied field reached critical field [3]. The pressure can be calculated by using the arithmetic of Monte-Carlo or finite element methods [4], [5].

III. Design of Motor Configurations

Different driving configurations may get different results. Four driving configurations such as 2-phase 1-pole, 3-phase 1- pole, 4-phase 1- pole and 2-phase 2- pole are shown in Fig. 1 and Fig. 2. As presented in Fig. 2, the niobium tube is located in the center of the rotor and with some slotted openings (windows) at the same level of the driving coils. The numbers of these windows equals the numbers of the poles. Magnetic flux lines from the stator pass through the windows, causing forces to be applied against slotted openings of superconducting niobium tube [9]. If the forces applied on the two edges of the window are different, the rotor will be driven.

The difference of flux density between the two edges of the window can cause a force to rotate the rotor, and different driving configurations may yield different diamagnetic force. Along the x axis shown in Fig. 2, the flux density can be calculated at different distance. Fig. 3 shows the distribution of magnetic flux density when the exciting current applied on the coils of the four driving configurations is $400\ \mathrm{A/mm^2}$. It is

1051-8223/$20.00 © 2006 IEEE

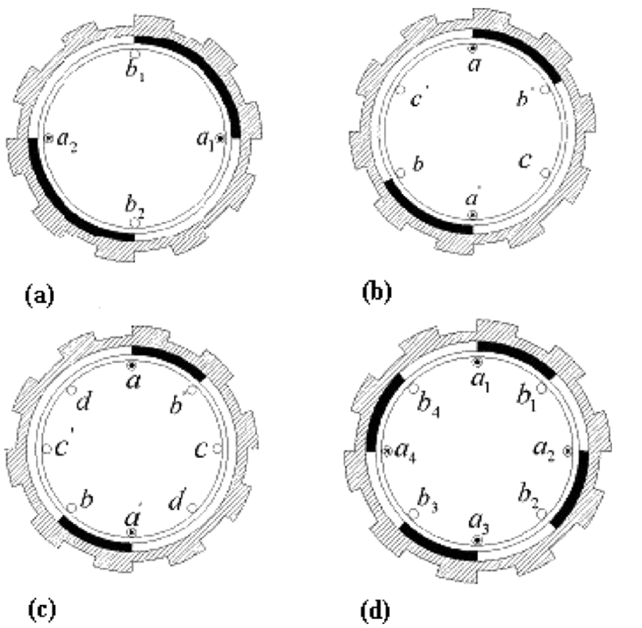

Fig. 1. Different driving mode for superconducting rotor and stator. a) 2-phase 1-pole. b) 3-phase 1-pole. c) 4-phase 1-pole. d) 2-phase 2-pole.

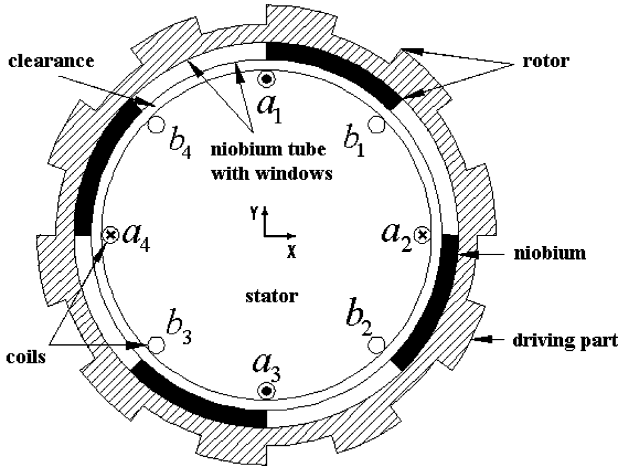

Fig. 2. Detailed configuration in the two-phases with two-poles motor.

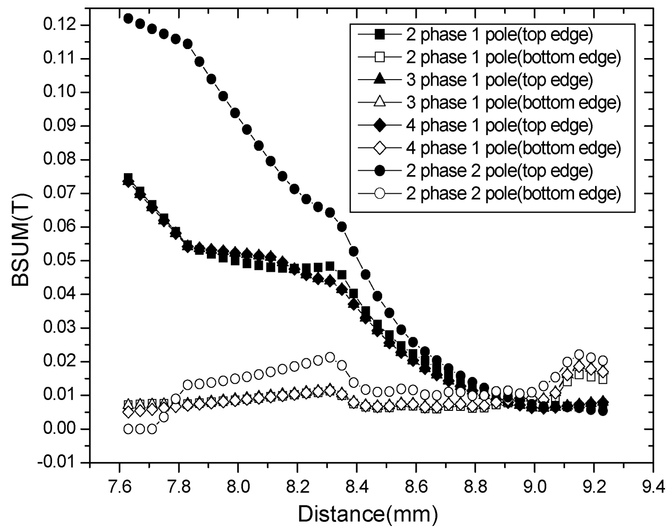

Fig. 3. Flux distribution of the 4 driving structures.

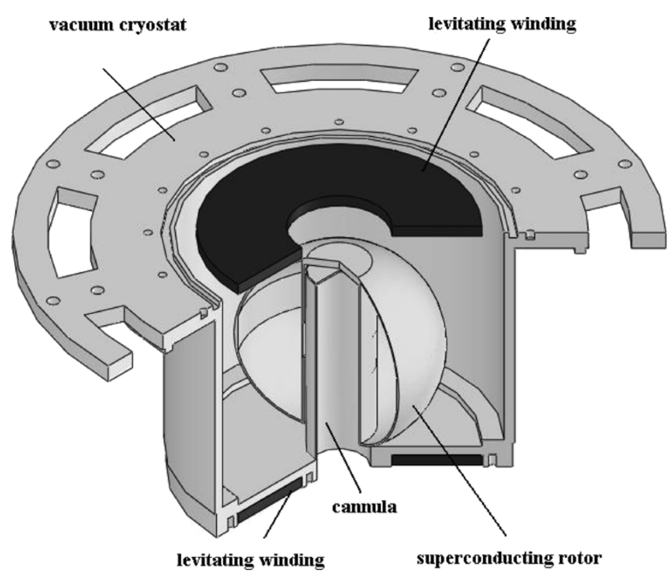

Fig. 4. The structure of the superconducting motor without stator.

possible to compare the driving effect of the four configurations based on the difference of flux density. As shown in Fig. 3, it can be seen that the average difference of flux density of the 2-phase 2-pole configuration between the two edges of the window is 0.05 T (500 G), but it is only about 0.03 T (300 G) for other configurations with the same exciting current.

It is clearly that more poles can achieve better driving effect, but one must be noted that more poles may bring more troubles to the power supply and control circuit, and also increase inductance of the driving coils.

The motor presented in this paper is different from the conventional motors. As shown in Fig. 4, the superconducting motor is located in the center of the vacuum cryostat without stator. This vacuum cryostat is immerged in liquid helium, the rotor can be cooled down to 4.2 K and becomes superconductor. When the levitating windings are powered, the rotor will be levitated by diamagnetic force. This suspension is inherently stable, entirely free of wear, and almost without losses. A pulse-operated driving coil used to accelerate the rotor can be installed in the cannula as shown in Fig. 4. Two torquer units are used to erect the rotor at the beginning and during spin-up and also used to develop error compensation torques.

The driving coil and torquer units must be installed in a flexible frame, so the disassembly of the motor system can be easily achieved.

IV. Analysis and Characters of the Motor

To simplify the drive and control circuit and to get an efficient driving configuration, the 2-phase 2-pole fabrication is selected to form our experimental motor.

Fig. 5 shows a spherical rotor of the motor with the diameter of 25 mm. The main structure of the rotor is a hollow quartzose ball covering with purity niobium shell. As the induced current associated with diamagnetic force flows within the thickness of 10^{-4} mm of the niobium only, the quartzose and a thin niobium

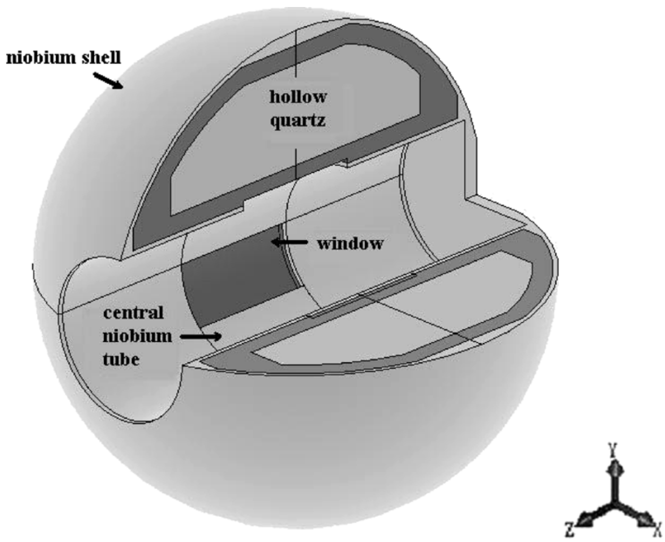

Fig. 5. Configuration of the superconducting rotor.

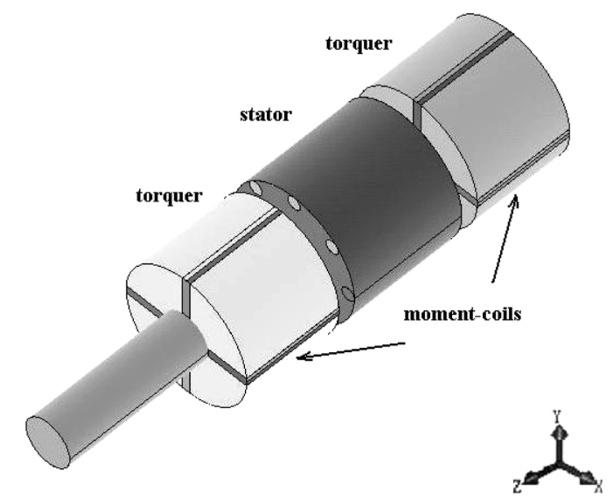

Fig. 6. Configuration of the central pillar.

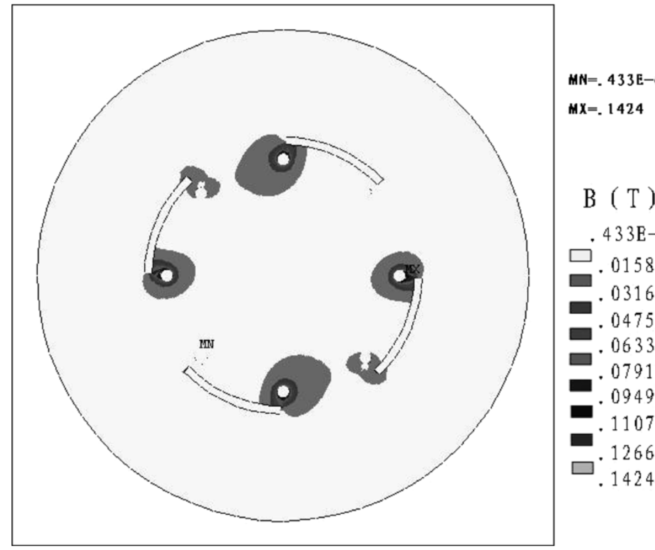

Fig. 7. Cross section of the stator windings in the niobium tube when the exciting current is applied on driving coils.

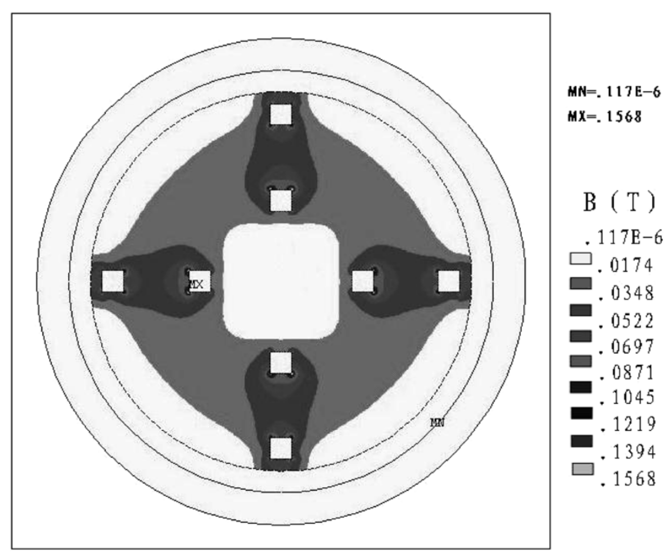

Fig. 8. Cross section of the torquer in the niobium tube when the exciting current is applied on four coils.

shell can be used to construct the rotor decrease the weight of the rotor. A niobium tube with windows is installed inside the hole of the rotor. The thickness of this tube is 0.8 mm. The treatment and precision of the rotor have much influence on performance of the motor.

Fig. 6 shows the configuration of the central pillar. A stator is in the center part of the pillar, it consists of a frame and driving coils, there are two torquer units on two sides of the stator, each unit consists of four coils oriented to produce torques about the X and Y axes.

The height of the torque coils is 10 mm, the effective height of the driving coils is 10 mm and its effective diameter is 0.8 mm. the clearance between the rotor and the stator is only 0.5 mm. The center pillar is airproofed by a brass tube which thickness is 0.5 mm. The cross section of the torque coil is a square with an area of $1 \times 1\ \mathrm{mm}^2$. The moment of inertia of the rotor is $4.1712 \times 10^{-4}\ \mathrm{N} \cdot \mathrm{m}^2$.

Driving coils are installed in the frame, and wound layer by layer. Exciting current will flow inside these coils and set up a field symmetrically from zero to full value to start driving. This is useful to drive the rotor quickly and placidly. It must be noted that the applied current is an alternating current with the high frequency, the attention has to be paid on the inductance and therefore the coil design and wire parameters.

The torquers are also working according to the principle of Meissner effect. Eight coils are fixed in the center pillar, when current flows through the coils, the field will cause force against surrounding surface of the superconducting niobium tube. As the central pillar is fixed, the rotor will be erected by this force. When all the coils are excited equally, these vectorial torques will add to zero and the rotor axis will parallel to the torquer axis. During rotor evaluation, the torquers are also used to compensate for error torques.

Analysis on motor and torquer is carried out with finite element method. Driving coil and torque coils are supplied by different power. The driving windings on the stator is serieswound, two coils are excited respectively, while the exciting current on one driving coil is $400\ \mathrm{A/mm^2}$ and the other is grounded, the distribution of magnetic flux density is shown in Fig. 7. Form the color listed, the value of B can be read out. Using the formula discussed in Section II, the coil will cause an average driving torque of $0.2779 \times 10^{-3} N \cdot m$. The maximum value of B is $0.1424\, T$, that below the critical magnetic field of niobium. The eddy currents will produce drag force which can reduce the driving force [11]. The effect of drag force on the motor will be examined in future studies.

As to the torquer, when the exciting current on torque coils is $270\ \mathrm{A/mm^2}$, the distribution of magnetic flux density is shown in Fig. 8. Different color represent different B value. The coil will cause an average erect torque of $0.5850 \times 10^{-3} N \cdot m$. The field around the torquer is also below the critical magnetic field. In the figure, it can be seen that a litter part of the whole flux produced by the torquer can be used to erect the rotor. Future work will be conducted by improving the configuration of the motor in order to use the flux efficiently.

V. Conclusion

A new type of superconducting motor for accurate and steady driving has been presented. The levitating and driving are achieved by diamagnetic force. The stator is located in the center of the rotor with two-phase two-pole driving windings.

The motor runs at low temperature and the rotor levitated spin in vacuum condition. If the rotor is driven, it will be working till a very long time without vibration.

The rotor is made from quartzose and high purity niobium, and niobium is used to form a shell. The results described above show that with the same exciting condition, the driving effect is determined by the number of the poles of the stator and the phases of the driving coils, and must be correspond to the power supply and control circuit. Further work is in progress to enhance the driving effect and accuracy of the motor.

References

[1] T. A. Buchhold, "The magnetic forces on superconductors and their applications for magnetic bearings," *Cryogenics*, pp. 203–211, Jun. 1961.

[2] Y. Zhang, *Superconducting Physics*. : USTC Press, 1997, pp. 40–50.

[3] A. Rivetti, G. Martini, R. Goria, and S. Lorefice, "Turbine flowmeter for liquid helium with the rotor magnetically levitated," *Cryogenics*, vol. 27, pp. 8–11, Jan. 1987.

[4] S. Mandayam, L. Udpa, S. S. Udpa, and W. Lord, "Monte Carlo methods for modeling magnetostatic NDE phenomena: A feasibility study," *IEEE Trans. Magn.*, vol. 32, pp. 1425–1428, May 1996.

[5] C. Cordier, S. Flament, and C. Dubuc, "A 3-D finite element formulation for calculating Meissner currents in superconductors," *IEEE Trans. on Appl. Supercond.*, vol. 9, no. 1, pp. 2–6, Mar. 1999.

[6] P. Masson, D. Netter, J. Leneque, and A. Rezzoug, "Magnetic field concentration: comparison between several shapes of superconducting shields," *IEEE Trans. on Appl. Supercond.*, vol. 11, pp. 2248–2251, Mar. 2001.

[7] I. Márquez, X. Granados, and X. Obradors, "Radial and axial flux superconducting motors in a levitating rotor configuration," *IEEE Trans. on Appl. Supercond.*, vol. 9, pp. 1249–1252, 1999.

[8] A. Takeoka, A. Ishikawa, M. Suzuki, and Y. Kuwano, "Meissner motor using high-Tc ceramic superconductors," *IEEE Transactions on Magnetics*, vol. 25, no. 2, pp. 2511–2514, Mar. 1989.

[9] K. F. Schoch and B. Darrel, *A Superconducting Gyroscope for Gimbaled Platform Application*. New York: General Electric Company Schenectady, pp. 657–665.

[10] J. T. Harding, *Drift Data for the Cryogenic GYRO,* California, Jet Propulsion Laboratory Pasadena, vol. P-7, pp. 137–143.

[11] Y.-K. Kim, M. Katsurai, and H. Fujita, "Fabrication and testing of a micro superconducting actuator using the Meissner effect," *Proc. IEEE Micro Electro Mechanical Systems,* Napa Valley, CA, pp. 61–66, 1990.