Design of the Magnetic Circuit to Improve Stability of the Magnetic Bearing Using HTS

Marin Minamitani¹, Satoshi Takimura¹, Shunsuke Ohashi¹

¹Department of the Electrical and Electric Engineering, Kansai University, 3-3-35, Yamate-cho, Suita, Osaka, Japan

k242369@kansai-u.ac.jp

Abstract. This paper proposes the design of the magnetic circuit to improve stability of the magnetic bearing using HTS. From the rotational characteristic, it is shown that if the flux of the rotor is concentrated to the outer part of the HTS, the rotor will be able to rotate stability. In order to achieve stable rotation, the yoke equipped ring type rotor is proposed. The ring type permanent magnet equipped the yoke is used of this rotor. The change in the flux when the gap between the yoke and the permanent magnet, the yoke thickness and the width are changed is considered. As each value increases, the flux amount increases. As the gap between the yoke and the permanent magnet increases, the flux distribution is more concentrated to the outer part of the HTS. Considering the overall diameter, the boundary where the increasing rate decreases is adopted as the optimum value. In the yoke thickness and the width, the minimum value where the magnetic saturation is not observed is adopted as the optimum value. As a result, the magnetic circuit that the flux is concentrated to the outer part of the HTS is designed. By concentrating the flux to the outer part of the HTS, the stable rotation is given.

1. Introduction

The magnetic bearing using the High Temperature Superconductor (HTS) has been developed. The mechanical bearing has the problems with friction, noise and energy loss. Furthermore, it requires periodic maintenance. The magnetic bearing solves these problems. The magnetic bearing supports the rotor in non-contact with magnetic force, so that friction dose not occurs. Therefore, there is no energy loss, and the maintenance becomes easy. By using this magnetic bearing, it is able to use in a vacuum or a special environment. In the ordinary magnetic bearing, the current control is required. Thus, the magnetic bearing using the pinning effect of the HTS have been developed. Using the pinning effect of the HTS, the rotor is stably supported in non-contact and uncontrolled [1], [2].

In this research, the magnetic bearing using the HTS is studied. The rotor composed of the permanent magnet is supported by the pinning force of the HTS. The magnetic levitation using the pinning force of the HTS is effective for achieving uncontrolled and stable levitation. By levitating the rotor in non-contact manner, the friction less system is eliminated and the rotation efficiency is improved. The stability of the rotor in the magnetic bearing during the rotation is important for application to the flywheel power storage system [3],[4].

This paper proposed the design of the magnetic circuit to improve stability of the magnetic bearing using HTS. The magnetic circuit of the 2-layer ring type rotor consists of the cylinder type permanent magnet and the ring type one. In this rotor, the part of the flux from the permanent magnet does not
interlink to the HTS [5]. Thus, the yoke equipped cylinder type rotor is introduced. In the magnetic circuit of this rotor, the iron is installed around the permanent magnet to concentrate the flux on the HTS [6]. The rotational characteristic of these two rotors are measured. The vibration of the yoke equipped cylinder type rotor is larger compared with that of the 2-layer ring type rotor. This is because the flux of this rotor is concentrated to the center of the HTS [7].

The flux distribution on the surface of the HTS is related to the stability of the rotor during rotation. When the flux is concentrated to the outer part of the HTS, stable rotation is maintained [7]. In order to achieve more stable rotation, the yoke equipped ring type rotor is proposed. This rotor is used the ring type permanent magnet equipped the yoke. The magnetic circuit of this rotor is designed using magnetic field analysis of the three-dimensional finite element method.

2. Experimental method

Figure 1 shows the structure of the magnetic bearing. The HTS on the stator side, and the rotor on the rotor side are used in this magnetic bearing system. In this experiment, the rotor is levitated using the pinning effect by the HTS. The HTS is installed on the aluminium stage, and the acrylic plate for spacer which have 10 [mm] gap is installed on the HTS. The rotor is installed on the spacer and set the center of the HTS. Liquid nitrogen into the aluminium vessel until the HTS is immersed, and cool in a magnetic field is poured for 30 minutes (field cooling). After cooling is complete, the spacer is removed and then the rotor levitates [6]. The levitation gap is $g = 10$ [mm]. Table 1 shows the specification of the HTS. The principle of HTS magnetic bearings is directly applied to flywheel. This system is considered to be installed in vehicles such as automobiles or trains.

![Figure 1. Structure of the magnetic bearing](image)

Table 1. Specification of the HTS

| Material               | YBaCuO |
|------------------------|--------|
| Manufacturer           | Nippon Steel |
| Critical temperature [K]| 91     |
| Dimension [mm]         | 80     |
| Thickness [mm]         | 20     |

Figure 2 shows the magnetic circuit and the flux line of the 2-layer ring type rotor. This magnetic circuit is composed of the cylinder type permanent magnet and the ring type one. By 2-layer structures, the flux spreads widely and interlinks to the HTS. The flux above the permanent magnet dose not interlink to the HTS. Thus, the yoke equipped cylinder type rotor is considered. Figure 3 shows the magnet circuit and the flux line of the yoke equipped cylinder type rotor. This magnetic circuit composed of the cylinder type permanent magnet equipped the yoke. The yoke is made from iron SS400, a highly saturated magnetic flux density material (Saturation magnetic flux density $B_s = 1.95$[T]). By equipped the yoke, the flux above the permanent magnet is concentrated to the HTS. Table 2 shows the permanent magnet volume and the flux interlinked the HTS surface. From the table 2, the volume of the permanent magnet for the yoke equipped cylinder type rotor is almost half volume of that for the 2-layer ring type rotor. In these two rotors, the flux interlinked to the HTS surface is almost same.
2.1. Rotational characteristics

The rotational characteristic is examined. Figure 4 shows the experimental device. The rotational speed is measured using the non-contact tachometer, and displacement of the rotor is measured using the transmission laser. The rotational characteristic is measured until the vibration caused by the natural frequency of the rotor converges [7]. Figure 5 shows the rotational characteristic of the two rotors. From figure 5, the vibration of the yoke equipped cylinder type rotor is increased by 36.8% compared with that of the 2-layer ring type. The rotational characteristic of the yoke equipped cylinder type rotor becomes worse even though the flux interlinked to the HTS of the two rotors are almost same. Figure 6 shows the flux density of the HTS surface. From figure 6, the flux of the 2-layer ring type rotor is concentrated to the outer part of the HTS. The flux of the yoke equipped cylinder type rotor is concentrated to the center of the HTS. In order to rotate stably, it is necessary to concentrate the flux to the outer part of the HTS. By concentrating the flux to the outer part of the HTS, the vibration is suppressed. It is shown that the distribution of the flux is related to the stability during rotation.
3. Magnetic field analysis

From figure 5, and 6, it is shown that the flux distribution of the HTS surface is related to stability of the magnetic bearing. In order to maintain stable rotation, the rotor of the magnetic bearing is produced. This rotor aims for stable rotation by concentrating flux to the outer part of the HTS. The magnetic circuit of the rotor is designed using magnetic field analysis of the three-dimensional finite element method. In this research, the yoke equipped ring type rotor is proposed. The ring type permanent magnet is used of this rotor to distribute the flux widely to the outer part of the HTS. This rotor equips the yoke to concentrate the flux to the HTS.

Figure 7 shows the magnet circuit of the yoke equipped ring type rotor. In this section, the change in the flux when the gap between the yoke and the permanent magnet \( w \), the yoke thickness \( a \) and the yoke width \( b \) are changed is considered.

3.1. Change the gap between the yoke and the permanent magnet \( w \)

In the magnetic circuit of the yoke equipped ring type rotor, the change in the flux when the gap between the yoke and the permanent magnet \( w \) is changed is considered. The analysis is performed under these conditions, the outer diameter of the ring type permanent magnet is 64 [mm], the inner diameter is 24 [mm], and the levitation gap is 10 [mm]. Figure 8 shows the flux density characteristic. Figure 9 shows the flux characteristic. Figure 10 shows the flux line.
From the figure 8 ~ 10, as the gap \( w \) increases, the flux amount increases. And the flux distribution is more concentrated to the outer part of the HTS. From the figure 9, the \( z \) - axis direction component of the flux increases monotonically. The increasing rate of the \( r \) - axis direction component decreases after \( w = 6 \) [mm]. As the gap \( w \) increases, the diameter of the rotor increases. If diameter of the rotor is larger than that of the HTS, the part of the flux of the rotor dose not interlinked to the HTS. It makes that the pinning force becomes small, and it causes that the suppression force against vibration becomes small. As a result, the gap \( w = 6 \) is adopted.

3.2. Change the yoke thickness \( a \)
The change in the flux when the yoke thickness \( a \) is changed is considered. From the result of the previous section, the gap between the yoke and the permanent magnet is \( w = 6 \) [mm]. The levitation gap is \( g = 10 \) [mm]. Figure 11 shows the flux density characteristic. Figure 12 shows the flux characteristic. Figure 13 shows the flux line. Figure 14 shows the flux density of the rotor.
From figure 11 and 12, as the thickness $a$ increases, the flux amount increases. From figure 13 and 14, when the thickness $a$ is small, the flux leaks from the upper surface of the yoke for the magnetic saturation. When the thickness $a$ is large, the flux above the permanent magnet is concentrated to the HTS side without the occurrence of the magnetic saturation. From figure 12, the flux increases in both axial directions in $a = 2 \sim 6$ [mm]. The flux is almost same at $a = 6 \sim 8$[mm], it shows that the magnetic saturation is suppressed at $a = 6$ [mm]. As a result, yoke thickness $a = 6$[mm] is adopted.
3.3. Change the yoke width \( b \)

The change in the flux when the yoke width \( b \) is changed is considered. From the result of the previous sections, the gap between the yoke and the permanent magnet is \( w = 6 \) [mm], and the yoke thickness is \( a = 6 \) [mm]. The levitation gap is \( g = 10 \) [mm]. Figure 15 shows the flux density characteristic. Figure 16 shows the flux characteristic. Figure 17 shows the flux line. Figure 18 shows the flux density of the rotor.
From figure 15 and 16, as the yoke width $b$ increases, the flux amount increases. From figure 17 and 18, when the width $b$ is small, the flux leaks from the side of the yoke for the magnetic saturation. The magnetic saturation does not occur by increasing the yoke width $b$. The flux is almost same in the $b = 5\sim 8$ [mm], and it shows that the magnetic saturation is suppressed at $b = 5$ [mm]. As width $b$ increases, the rotor becomes large. It causes that the suppression force against vibration becomes small. In consideration of the factors, yoke width $b=5$ [mm] is adopted.

The magnetic circuit is determined by analysis. When the scale of the system is expanded, it is necessary to perform the analysis again.

4. Conclusion
In this paper, the magnetic circuit of the rotor is designed to improve the stability of magnetic bearing. The flux distribution on the surface of the HTS is related to the stability of the rotor during rotation. When the flux is concentrated to the outer part of the HTS, stable rotation is maintained. In order to suppress the vibration, the yoke equipped ring type rotor is proposed. This rotor is consisted of the ring type permanent magnet equipped the yoke to concentrate the flux to the outer part of the HTS. The magnetic circuit of this rotor is designed. The change in the flux when the gap between the yoke and the permanent magnet, the yoke thickness and the yoke width are changed is considered.

As the gap between the yoke and permanent magnet increases, the quantity of flux increases. And the flux distribution is more concentrated to the outer part of the HTS. As the gap between the yoke and the permanent magnet and the yoke width increase, the rotor becomes large. It causes that the suppression force against vibration becomes small. Considering the overall diameter, the boundary where the increasing rate decreases is adopted as the optimum value. As the yoke thickness and the yoke width increase, the quantity of flux increases. The minimum value where the magnetic saturation is not observed is adopted as the optimum value. In consideration of the factors, the magnetic circuit that the flux is concentrated to the outer part of the HTS is designed. By concentrating the flux to the outer part of the HTS, the vibration is suppression and stable rotation is given.

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