NEW DESIGN OF HYBRID TYPE SELF-BEARING MOTOR FOR HIGH-SPEED MINIATURE SPINDLE

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ABSTRACT

A new structure of hybrid type self-bearing motor for miniature spindle motors is proposed. The rotor and the stator length are extended to have two parts: One is the permanent magnet part to produce motor polarity, and the other is the bypass magnetic circuit part made of soft iron to reduce the reluctance. The PM part mainly operates as a PM motor while the soft iron part operates as a hybrid type magnetic bearing. They are integrated in a rotor-stator pair in common. Therefore, the structure combines the hybrid type self-bearing motor with the hybrid active magnetic bearing in the common stator and rotor pair to generate large radial force.

An experimental miniature spindle motor was made to confirm the new design. The system has 36[mm] rotor diameter, 41.5[mm] rotor length and five axis control capability with built-in micro displacement sensors. The results showed stable levitation, large levitation force and strong rotation. It is confirmed that the proposed designed is suitable for miniature spindle, and it can be applicable to a spindle motor for data storage devices.

INTRODUCTION

For high rotating speed, high power and clean-environment applications, magnetic bearings have been used to support rotors without physical contact. This requires a separate driving motor in addition to magnetic bearings, hence the rotor becomes long and is apt to produce bending vibration. The large motor-bearing system makes it unapplicable to small rotary machines. There are some studies to apply a magnetic bearing in a small motor [1],[2]. However, it seems that more miniaturization is difficult because three stator is required. To overcome these problems, several types of self-bearing motor have been introduced which combine a rotary motor with a magnetic bearing [3],[4].

In previous studies, a hybrid type self-bearing motor is proposed [5],[6]. in which the rotor has two functions of rotary motor and radial magnetic bearings. The hybrid type self-bearing motor uses DC magnetic flux to control radial force. The radial force and the rotating torque are independent when the pole pair number is greater than 3. Hence, the structure of the self-bearing motor and its control system can be simplified. In addition, the permanent magnets produce the bias flux, and the electro magnets produce only the control flux. Therefore, power consumption is small, making it suitable for small spindle applications.

The problem with this motor is that motor permanent magnets are glued on the surface of the rotor which increases the reluctance of magnetic bearing circuit and reduces the levitation force. In particular, when applied to the spindle motor of computer storage devices, the low levitation force causes serious problems.

In this study, a new structure of hybrid type self-bearing motor for miniature spindle motors is proposed. The rotor and the stator length are extended to have two parts: One is the permanent magnet part to produce motor polarity while the other is the bypass magnetic circuit part made of soft iron to reduce the reluctance. The PM part mainly operates as a PM motor while the soft iron part operates as a hybrid type magnetic bearing. They are integrated in a rotor-stator pair in common. Therefore, the structure combines the hybrid type self-bearing motor with the hybrid active magnetic bearing in the common stator and rotor pair to generate large radial force.

First, the principle and theoretical background are introduced. Then, the air gap flux is analyzed by finite element method (FEM) and the radial forces in the proposed and standard hybrid type self-bearing motor are compared. The results show that the

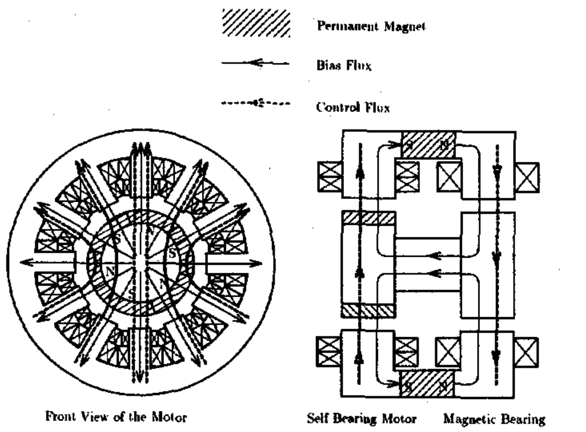

FIGURE 1: Schematic diagram of hybrid type self-bearing motor

new structure is effective for increasing the levitation forces.

To develop a small, high-performance miniature spindle motor, an outer rotor type motor is designed and fabricated. To realize five axis controlled miniature self-bearing motor, an axial active magnetic bearing is integrated into the bias flux circuit of the hybrid type self-bearing motor. A high accuracy eddy current type micro displacement sensor is also developed and installed to the proposed motor.

An experimental miniature spindle motor was made to confirm the new design. The system has 36[mm] rotor diameter, 41.5[mm] rotor length and five axis control capability with built-in micro displacement sensors. The results showed stable levitation, large levitation force and strong rotation. It is confirmed that the proposed designed is suitable for miniature spindle, and it can be applicable to a spindle motor for data storage devices.

HYBRID TYPE SELF-BEARING MOTOR

Figure 1 shows the schematic drawing of the basic structure of the hybrid type self-bearing motor. The right side of Fig. 1 indicates two components; the left side is the self-bearing motor, while the right side is the hybrid type magnetic bearing. Between them a permanent magnet is installed which gives the bias flux as shown by the solid arrow line.

The front view indicates the construction of the self-bearing motor. The stator has two kinds of winding: one is for levitation control and the other is for rotation. There are two levitation coils for the x and y directions, both of which are two-pole windings. These produce the control flux as shown by the dotted line in the left side of Fig. 1 and produce radial force. The rotation can be controlled by means of the conventional permanent magnet motor.

This type of self-bearing motor has been analyzed theoretically and independent control has been derived when the motor pole pair number is greater than three [5],[6]. The analytical results are summarized below.

The air gap flux densities generated by rotor magnet B_r, motor windings B_{sm} and levitation windings B_{sb} are approximately expressed as follows:

$$B_r = B_0 + B_1 \cos(M\theta - \omega t) \quad (1)$$
$$B_{sm} = B_2 \cos(M\theta - \omega t - \psi) \quad (2)$$
$$B_{sb} = B_3 \cos(\theta - \phi) \quad (3)$$

Thus, the total flux distribution B_g in the air gap is given by

$$B_g = B_r + B_{sm} + B_{sb} \quad (4)$$

where

B_0	:	average bias flux density produced by bias permanent magnet
B_1	:	peak flux value produced by rotor permanent magnet
B_2	:	peak flux value produced by motor current
B_3	:	peak flux value produced by levitation current
θ	:	angular coordinate on the stator
ψ	:	motor flux phase
ϕ	:	levitation flux phase
ω	:	angular velocity of the rotor
t	:	time
M	:	pole pair number $(= 1, 2, 3, \cdots)$
r	:	rotor radius
g	:	air gap between the rotor and the stator
l	:	rotor length

If the pole pair number is greater than three, the x, y directional forces F_x, F_y and rotating torque T are calculated and given by the following equations:

$$F_x = \frac{B_0 B_3 l r \pi}{\mu_0} \cos(\phi) \quad (5)$$
$$F_y = \frac{B_0 B_3 l r \pi}{\mu_0} \sin(\phi) \quad (6)$$
$$T = -\frac{r l g M B_1 B_2 \pi}{\mu_0} \sin M\psi \quad (7)$$

NEW STRUCTURE OF THE MOTOR-BEARING

A miniature spindle motor is considered here. Maximum rotating torque T is determined by the design specification of the spindle. According to equation (7), the peak flux value produced by rotor permanent magnet B_1 should be large when the peak motor flux B_2 is limited. Therefore, the surface permanent magnet of the rotor should be strong and thick.

Next, consider the levitation force. According to equations (5) and (6), the average bias flux density produced by bias permanent magnet B_0 and the peak flux value produced by levitation current B_3

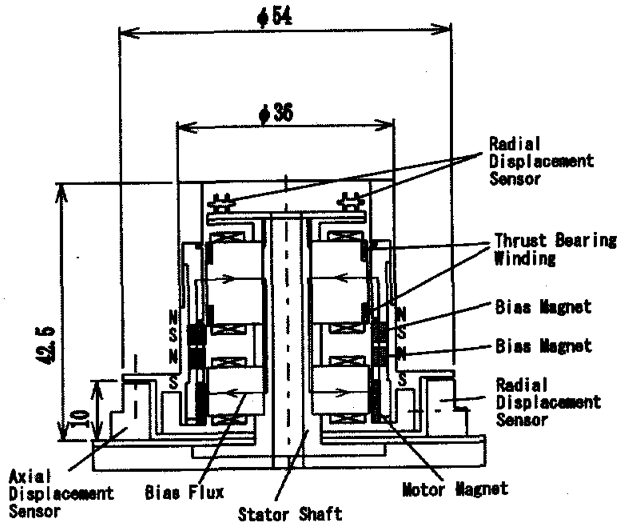

FIGURE 2: Schematic of new structure 5 axis controlled hybrid type self-bearing motor

should be large to obtain large levitation forces F_x, F_y. Hence the reluctance of the magnetic bearing circuit should be small and the air gap between rotor and stator should be small. These two requirements conflict each other.

To overcome this problem, a new structure is proposed as shown in Fig. 2. There are two rotor-stator pairs: upper one is for hybrid type AMB and lower one is for self-bearing motor. They are connected magnetically to make a bias magnetic circuit.

On the surface of the lower rotor, 8-pole ring permanent magnets are glued to produce the motor polarity. The rotor and the stator length of the self-bearing motor are extended to have two parts: One is the permanent magnet part to produce motor polarity while the other is the bypass magnetic circuit part made of soft iron to reduce the reluctance. The PM part mainly operates as a PM motor while the soft iron part operates as a hybrid type magnetic bearing. They are integrated in a rotor-stator pair in common. Two bias magnets are installed between them to produce the bias magnetic flux as shown by the dotted line.

The air gap length between the rotor and the stator including rotor magnet is 2.6[mm] while the air gap length of bypass circuit parts is 0.6[mm].

Four eddy current type micro displacement sensors are installed inside the rotor to measure the upper x and y directional rotor positions. The lower radial rotor positions are measured by four eddy current type micro displacement sensors arranged on the base printed curcuit board. Each two opposit pair sensors are used differentially to improve precision.

The axial rotor position is also measured by an eddy current type micro displacement sensor arranged on the base printed circuit board.

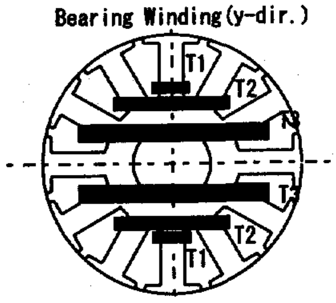

FIGURE 3: Schematic diagram of levitation coil of stator

Self-bearing motor stator structure

The stator is made of laminated sheet to reduce eddy current loss and has 12 slots.

The stator has two kinds of winding: one is for levitation control and the other is for rotation. Each slot has 34 turns concentrated windings for the motor. They are connected and driven by three-phase driver.

The levitation control windings are wound as shown in Fig. 3 to produce a sinusoidal flux density distribution. Turn numbers are: T_1 = 11, T_2 = 29 and T_3 = 40.

AMB stator structure

The upper stator has both functions of a radial hybrid type AMB and a thrust AMB. The stator is made of laminated sheet to reduce eddy current loss and has 4 legs. Two grooves are carved on the circumference of the stator to install the thrust coil.

The stator has two set of radial levitation control windings to generate x and y directional DC magnetic flux.

A windings of the thrust AMB are wound cylindrically along the grooves. Bcause the thrust AMB windings are placed orthogonally with the bias flux, an electrical current on the windings produce axial direction Lorentz force and axial position of the rotor can be controlled like a voice coil motor.

Self-bearing motor rotor structure

The schematic diagram of the rotor structure of the self-bearing motor is shown in Fig. 4. An 8-pole ring permanent magnet is glued to the lower inside the rotor surface. The back yoke has a bypass magnetic part which is upper than the permanent magnet. The self-bearing motor and the magnetic bearing rotor are joined with a yoke and bias permanent magnet, and are covered with an aluminum sleeve which is the target of the gap sensors.

The rotational angle is measured with the hole sensor and the rotor permanent magnet. This signal is used to control the rotation of the motor.

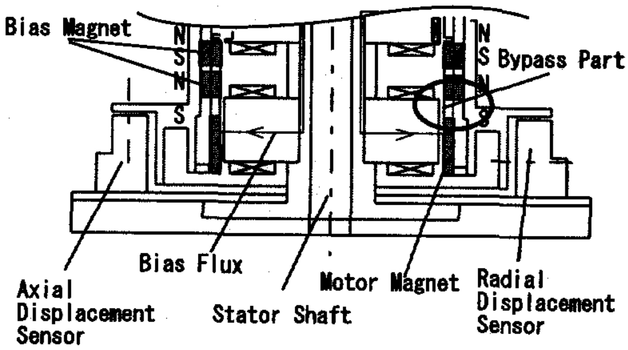

FIGURE 4: Schematic diagram of rotor structure

TABLE 1: Parameters of the conventional design and the proposed structures

	Proposed (With bypass)	Conventional design (Without bypass)
Core total thickness	6 [mm]	3.5 [mm]
Magnet length	3.5 [mm]	3.5 [mm]
Bypass part length	2.5 [mm]	0 [mm]

FLUX DENSITY SIMULATION

The considerable drawback of the proposed magnetic structure is magnetic short circuit between the motor permanent magnet and the bypass part. To evaluate the effect of this structure, FEM simulation was carried out. For simplicity, the flux density produced by the rotor permanent magnets and the flux density produced by the levitation coils were calculated separately.

The calculation results were compared for the proposed motor and the standard hybrid type self-bearing motor. The simulation parameters of the proposed and the conventional design motors are listed in Table 1.

Air gap flux density by permanent magnets

Figure 5 shows the flux density produced by rotor permanent magnet B_1 with and without the bypass magnetic part. The ring shape magnet for the motor is located from axial position $0[mm]$ to $3.5[mm]$. The flux values above the permanent magnets are almost the same, but the value above the bypass part decreases quickly.

Figure 6 shows the bias flux density produced by the bias permanent magnet B_0 with and without the bypass part. With the bypass part, the flux value B_0 above the ring permanent magnet decreases to 65% of the value without the bypass part. This is considered due to the effect of magnetic bypass. However,

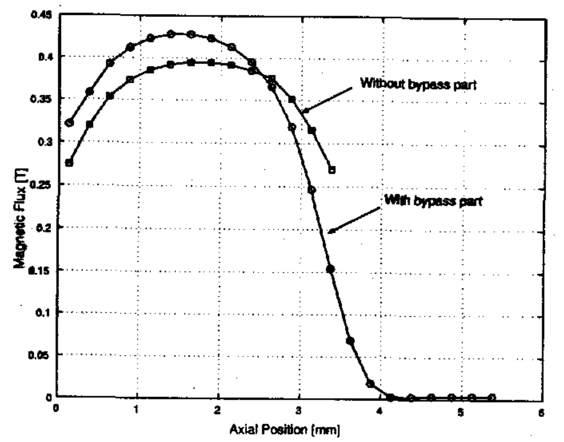

FIGURE 5: The flux density produced by rotor permanent magnet B_1

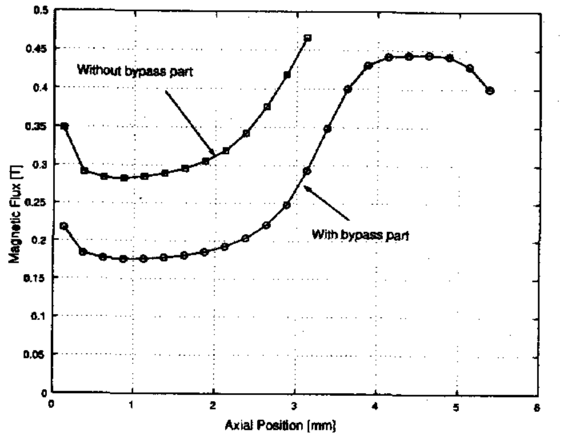

FIGURE 6: The bias flux density produced by the bias permanent magnet B_0

B_0 of the bypass part is 1.5 times higher than that of the ring shape magnet. This means that magnetic flux has concentrated on the bypass magnetic circuit part and the bearing force will be mainly produced on this bypass part.

Air gap flux density by levitation coils

Figure 7 shows the flux density in the axial direction produced by levitation current B_3 with and without the bypass part. The ring permanent magnet is located from $0[mm]$ to $3.5[mm]$. The difference of the value B_3 on the ring magnet is relatively small with and without the bypass part, while the value increases 3 times on the bypass part.

These results show that magnetic flux on the ring magnet is not disturbed even if the flux flows into the bypass part partially.

Finally, the levitation forces with and without the bypass part are calculated and shown in Table 2. The results show that the levitation force with the bypass part is 2.5 times greater than that without the bypass part. To install the bypass part, the stator length is increased to 1.7 times longer than that

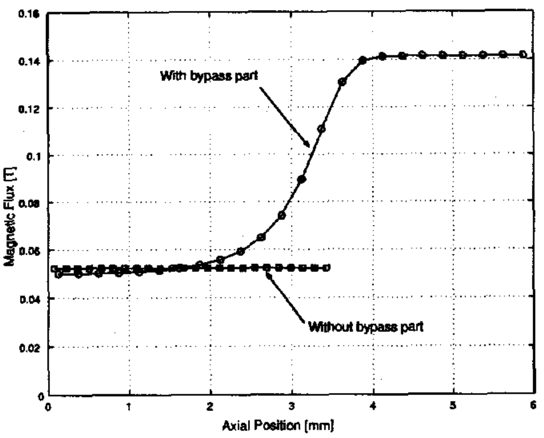

FIGURE 7: Axial magnetic flux density by levitation coil B_3

TABLE 2: Levitation force

	With bypass	Without bypass
Levitation force [N]	5.90	2.34

without the bypass part. However, the levitation force is increased more than the increase of the stator length. It shows that the bypass magnetic circuit is effective for increasing the levitation forces.

CONTROL SYSTEM

The schematic diagram of the control system is shown in Fig. 8. The motor windings are driven by a brushless DC motor driver IC (TOSHIBA TA7262P).

The levitation is controlled by a dSPACE DS1103 based on PowerPC processer. Radial displacements in the x and y directions of the upper and lower rotors and axial displacement are measured and input to DS1103 via A/D converters. Then the actuating signals are calculated using the standard PD controller for each direction separately and each coil current command is output to a power amplifier via D/A converter. A power op-amp TI OPA541 is used for the levitation control.

EXPERIMENTAL SETUP

To confirm the proposed new design, the experimental setup was made and the levitated rotating tests were permormed.

The photograph of the experimental setup is shown in Fig. 9.

In figure 9, the right side is the experimental motor, while the left side is a 3.5 inches HDD spindle motor for size comparison. A motor height is approximately 2 times higher then HDD spindle motor, but the diameter is almost equal.

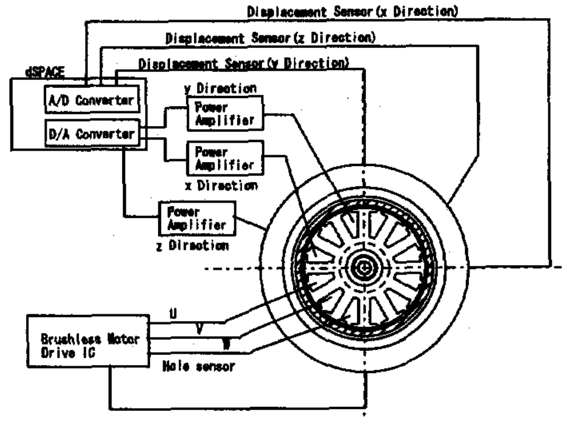

FIGURE 8: Schematic of control system

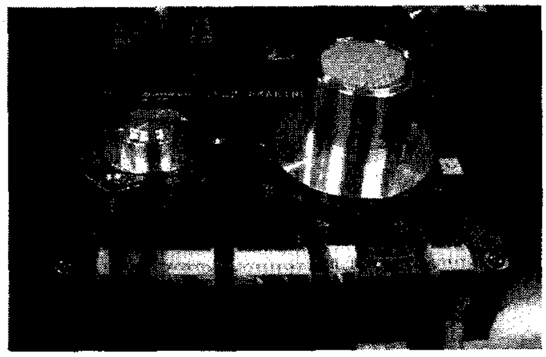

FIGURE 9: Photograph of a HDD spindle motor and the new designed motor

EXPERIMENTAL RESULTS

The control parameters for the levitaion controller are determined experimentally as listed in Table 3.

Levitation force

The radial levitation forces and the axial levitation force are measured by changing the levitation current and shown in Table 4.

Because the upper stator is AMB and the lower stator is self-bearing motor, the upper stator levitation force is apporoximately 1.5 times larger than the lower stator.

Rotating test

The no-load rotation test was carried out. The rotor can run over $10,000[rev/min]$ as shown in Fig. 10. The maximum rotating speed 10,000[rpm] is not due to the stability limit of levitation control, but due to the low voltage limit of the motor driver. The vibration amplitude of the y direction of upper rotor is 10 $[\mu m]$ larger than others over 8,000 $[rpm]$. However, they are very stable.

Motor characteristics

The torque constant is measured and compared with that of the 3.5" HDD spindle motor as shown in Table 5. The same ring permanent magnet is used

TABLE 3: Control parameters

K_p $[A/mm]$	15
K_d $[A\dot{s}ec/mm]$	0.0186
Derivative time $[\mu sec]$	400
Sampling time $[\mu sec]$	50

TABLE 4: Levitation forces

	Levitation force [N/A]
Upper stator	5.0
Lower stator	3.4
Axial	1.3

for both the proposed self-bearing motor and the HDD spindle motor. The torque constant of the proposed self-bearing motor is 19.25$[mNm/A]$ while the HDD spindle motor produces a torque constant of 14.5$[mNm/A]$.

This value is sufficient for practical small spindle motor applications.

CONCLUDING REMARKS

A new structure of hybrid type self-bearing motor for miniature spindle motors is proposed. The rotor and the stator length are extended to have two parts: One is the permanent magnet part to produce motor polarity while the other is the bypass magnetic circuit part made of soft iron to reduce the reluctance. The PM part mainly operates as a PM motor while the soft iron part operates as a hybrid type magnetic bearing. They are integrated in a rotor-stator pair in common.

It was analytically confirmed that the magnetic flux on the ring permanent magnet was not disturbed even if the flux flowed into the bypass part. The proposed bypass part was effective for increasing the levitation forces.

An experimental outer rotor type miniature spindle motor is designed and fabricated. To realize five axis controlled miniature self-bearing motor, an axial active magnetic bearing is integrated into the bias flux circuit of the hybrid type self-bearing motor. A high accuracy eddy current type micro displacement sensor is also developed and installed to the proposed motor.

Simple experiments were performed to confirm the performance of the proposed motor. The results showed stable levitation, large levitation force and strong rotation. It is confirmed that the proposed design is suitable for miniature spindle, and it can be applicable to a spindle motor for data storage devices.

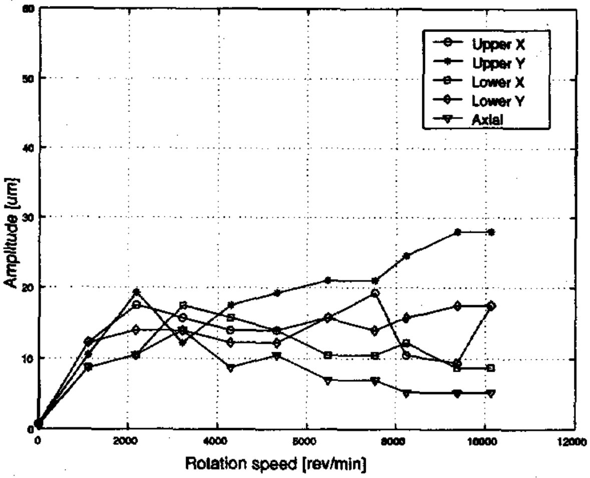

FIGURE 10: Unbalance responses

TABLE 5: Motor characteristics

	Torque Const. $[mNm/A]$	Mag. length $[mm]$	Winding $[turn]$
HDD Motor	14.5	3.5	61
New Design	19.25	5.66	34

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