DEVELOPMENT OF THE MINIATURE ACTIVE MAGNETIC BEARING WITH 6 CONCENTRATED WOUND POLES

Satoshi Ueno
Department of Mechanical Engineering, Ritsumeikan University,
Nojihigashi 1-1-1, Kusatsu, Shiga-Pref., 525-8577 Japan
sueno@se.ritsumei.ac.jp

Takayuki Arai, Kinya Odagiri
Namiki Precision Jewel Co., Ltd.,
Kuroishi, Aomori-Pref., 036-0539 Japan

ABSTRACT

This paper introduces design and control of a miniaturized radial active magnetic bearing (AMB) aiming the improvement in durability and noise reduction of small motors. The purpose of this research is to develop miniaturized practical AMB so that it can be applicable to the small motor. The proposed AMB, which is inner rotor hetero polar type. Generally, the stator has 8 poles. However fewer pole numbers leads to lower cost of AMB, but disadvantage is low bearing force. In order to balance the cost and the bearing force, the pole number was set to 6. Then, the control of the bearing force is introduced. In order to reduce energy consumption, the minimum energy control method is developed. In this method, coil currents are calculated from a simple magnetic circuit so that the copper loss in a coil may become minimum. Finally, the prototype motor is fabricated using the proposed AMB.

INTRODUCTION

Recently, demand of improving in durability and noise reduction for small motors is increasing [1, 2, 3]. Several types of small motor using active magnetic bearing have been proposed. However AMB does not become popular because the bearing force of AMB is small compared with mechanical bearings and AMB is expensive. Magnetic bearings have advantages such as no friction loss, no abrasion, lubrication free operation and so on. Therefore, miniaturization and cost reduction of AMB is required.

The self-bearing motor, which has both functions of a brushless motor and an active magnetic bearing has been developed for the miniaturization of rotating system [3, 4]. The self-bearing motor has merits of miniaturization, but it requires complex stator construction and control system. In order to reduce cost, passive type magnetic bearing which utilize the permanent magnet has been developed [5, 6]. It can dramatically reduce cost, but it does not have enough damping in the passive directions. The purpose of this research is to develop miniaturized practical AMB so that it can be applicable to the small motor.

In this paper, 6-pole AMB is proposed to realize miniaturization and cost reduction. Usually, pole number of the stator is designed over 8. However bigger pole number causes increase of manufacturing cost and difficulty in miniaturization. Therefore, pole number of the stator is reduced to 6, and it aims to compatible miniaturization with cost reduction.

A new control method is developed. Generally, magnetic force is linearized by supplying bias currents to a pair of electromagnets which face each other. However, this method must always supply bias currents, and the energy consumption becomes large. To solve this problem, non-linear control technique [8] and hybrid type magnetic bearing [9] were proposed. Hybrid type magnetic bearing is recognized as an efficient one and has good dynamic property. But the bias permanent magnet should be installed between the two radial magnetic bearings, and this requires large and heavy structure. In this paper, the minimum energy control method is developed. In this method, coil currents are calculated from a simple magnetic circuit so that the copper loss in a coil may become a minimum. This method is confirmed by a simple experiment.

Finally, the prototype motor is fablicatedusing the proposed AMB.

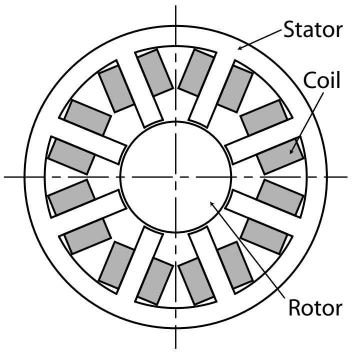


Figure 1: Schematic of Active Magnetic Bearing

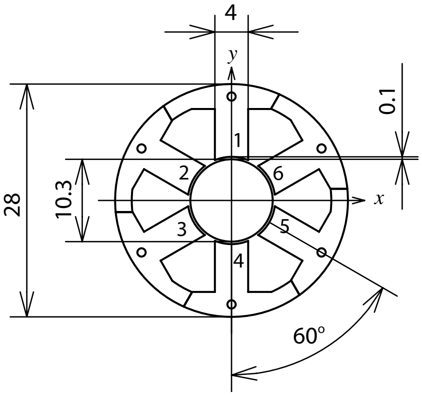


Figure 2: Geometry of proposed 6-pole AMB

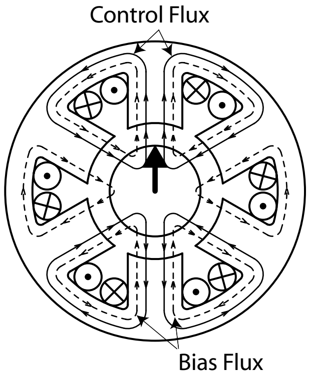


Figure 3: Bias current control

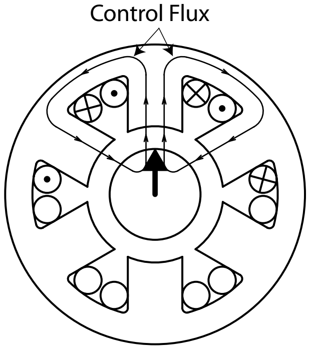


Figure 4: Minimum energy control

6-POLE ACTIVE MAGNETIC BEARING

Figure 1 shows the structure of the general heteropole active magnetic bearing. It has 8-pole and 8 coils. The bearing force is generated by currents of the coil. This structure has merits of the simple control system because the vertical and horizontal forces can be controlled independently. However, the manufacturing cost of the stator is high and fewer coil number is better for cost reduction.

On the other hand, fewer pole number causes less coil space and small maximum bearing force. One of the reason is that the magnetic flux par one pole becomes large, then back yolk must be thick to avoid magnetic saturation and the coil space becomes smaller. Then the maximum bearing force becomes smaller.

In this paper, to balance the manufacturing cost and the maximum bearing force, 6-pole number is selected. The geometry of the proposed 6-pole AMB is shown in figure 2.

MINIMUM ENERGY CONTROL

The control method of the bearing force is discussed. Generally, the bias current is used for the linearization of bearing force. This method can be applied to the 6-pole AMB as shown in figure 3. However it has disadvantage of power consumption due to bias current. In order to reduce the power consumption, the minimum energy control method is introduced. Coil currents are calculated from simple bearing force model in order to minimalize total copper loss as shown in figure 4. The control currents are derived from the relationship between the bearing force and coil currents. In order to simplify analysis, the displacements of the rotor are assumed to be zero, and the magnetic resistance of the core and the leakage flux are neglected.

Modeling

The coordinate axes of the proposed 6-pole AMB are defined as figure 5 The number of poles are defined as the direction of y to 1, and 2, 3, $\cdots$, 6 are defined along counterclockwise. The magnetic attractive force of each pole are defined as $f_1, \cdots, f_6$, and the bearing force to x, y direction are defined as f_x, f_y. The positive direction of current is defined as generating flux toward to the rotor direction. The magnetic circuit can be modeled as shown in figure 6, where Φ_K is flux, N is number of coil turn, i_K

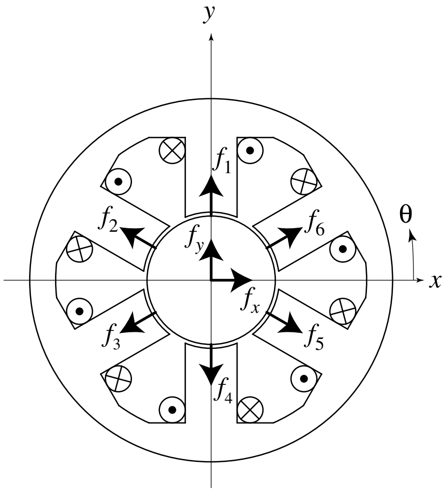


Figure 5: Coordinate Axes

is coil current and subscript K is the pole number.

We assume that displacements of the rotor are zero, then magnetic resistance of the air gap is written as

$$R_{gK} = \frac{g_0}{\mu_0 S} \tag{1}$$

where μ_0 is magnetic permeability of air, S is the cross-sectional area of the magnetic path, and g_0 is the air gap between the rotor and the stator. From figure 6, the flux of each pole is derived as follows.

$$\begin{bmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \Phi_4 \\ \Phi_5 \\ \Phi_6 \end{bmatrix} = \frac{\mu_0 S N}{6 g_0} \begin{bmatrix} -1 & 5 & -1 & -1 & -1 & -1 \\ -1 & -1 & 5 & -1 & -1 & -1 \\ -1 & -1 & -1 & 5 & -1 & -1 \\ -1 & -1 & -1 & -1 & 5 & -1 \\ -1 & -1 & -1 & -1 & -1 & 5 \\ 5 & -1 & -1 & -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix} \tag{2}$$

Hence, the flux density is calculated by dividing equation (2) by S,

$$B_K = \frac{\Phi_K}{S} = \frac{\mu_0 N}{g_0}\left(i_K - \frac{i_0}{6}\right) \tag{3}$$

where i_0 is the sum of each coil current as

$$i_0 = i_1 + i_2 + i_3 + i_4 + i_5 + i_6 \tag{4}$$

Hence the following equation are formed.

$$B_1 + B_2 + B_3 + B_4 + B_5 + B_6 = 0 \tag{5}$$

The magnetic forces are described as

$$f = \frac{S B^2}{2\mu_0} \tag{6}$$

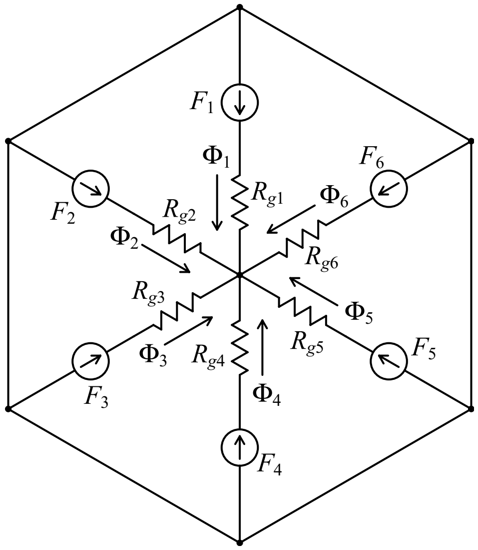


Figure 6: Magnetic Circuit

Hence, the attractive force of each pole f_K is

$$f_K = \frac{S}{2\mu_0} B_K^2 = \frac{\mu_0 S N^2}{2 g_0^2}\left(i_K - \frac{i_0}{6}\right)^2 \tag{7}$$

The bearing force x and y are the summation of the component of x and y direction of each attractive force. Hence the f_x and f_y are calculated as follows.

$$\begin{aligned} f_x &= \frac{\sqrt{3}}{2}(-f_2 - f_3 + f_5 + f_6) \\ &= \frac{\sqrt{3}S}{4\mu_0}(-B_2^2 - B_3^2 + B_5^2 + B_6^2) \end{aligned} \tag{8}$$

$$\begin{aligned} f_y &= f_1 - f_4 + \frac{1}{2}(f_2 - f_3 - f_5 + f_6) \\ &= \frac{S}{4\mu_0}(2B_1^2 + B_2^2 - B_3^2 - 2B_4^2 - B_5^2 + B_6^2) \end{aligned} \tag{9}$$

Coil Currents

Coil currents $i_1 \sim i_6$ are derived. The reference forces are defined as force command $\hat{f}_x$ and $\hat{f}_y$. The solutions which minimize the total copper loss in the coil is derived. The copper loss is written as

$$W_{loss} = \sum_{K=1}^{6} R i_K^2 \tag{10}$$

where R is resistance of coil. The performance index is defined as

$$J_i = i_1^2 + i_2^2 + i_3^2 + i_4^2 + i_5^2 + i_6^2 \tag{11}$$

and currents $i_1 \sim i_6$ which minimize J_i are derived. From equation (3), substituting i_K into equation (11), we have

$$J_i = \frac{g_0^2}{\mu_0^2 N^2}(B_1^2 + B_2^2 + B_3^2 + B_4^2 + B_5^2 + B_6^2) + i_0^2 \tag{12}$$

Now, J_i becomes minimum when

$$i_0 = i_1 + i_2 + i_3 + i_4 + i_5 + i_6 = 0 \tag{13}$$

Hence, the minimization problem of J_i changes to minimization problem of

$$J = B_1^2 + B_2^2 + B_3^2 + B_4^2 + B_5^2 + B_6^2 \tag{14}$$

The direction of force generated by B_1 is in the opposite direction of B_4. Hence in order to minimize J, the flux density of opposite side to the bearing force must be zero. The reference values of the bearing force are rewritten in polar form as

$$\hat{f} = \hat{f}_x^2 + \hat{f}_y^2 \tag{15}$$

$$\phi = \tan^{-1}(\hat{f}_y/\hat{f}_y) \tag{16}$$

From the structure of AMB, the flux density which becomes zero are derived as follows.

$$B_2 = B_3 = B_4 = 0 \qquad 0 \leq \phi < 60^\circ \tag{17}$$

$$B_3 = B_4 = B_5 = 0 \qquad 60^\circ \leq \phi < 120^\circ \tag{18}$$

$$B_4 = B_5 = B_6 = 0 \qquad 120^\circ \leq \phi < 180^\circ \tag{19}$$

$$B_5 = B_6 = B_1 = 0 \qquad 180^\circ \leq \phi < 240^\circ \tag{20}$$

$$B_6 = B_1 = B_2 = 0 \qquad 240^\circ \leq \phi < 300^\circ \tag{21}$$

$$B_1 = B_2 = B_3 = 0 \qquad 300^\circ \leq \phi < 360^\circ \tag{22}$$

Next, coil currents are derived. In case of $0 \leq \phi < 60^\circ$, bearing forces are rewritten from equations (5), (8), (9) and (17) as follows

$$\hat{f}_x = \frac{\sqrt{3}S}{4\mu_0}(B_5^2 + B_6^2) \tag{23}$$

$$\hat{f}_y = \frac{S}{4\mu_0}(2B_1^2 - B_5^2 + B_6^2) \tag{24}$$

$$0 = B_1 + B_5 + B_6 \tag{25}$$

Solving simultaneous equations of (23), (24) and (25), we have

$$B_5 = \pm\sqrt{\frac{2\mu_0}{S}\left(\frac{7\sqrt{3}}{15}\hat{f}_x - \frac{1}{5}\hat{f}_y - \frac{2\sqrt{3}}{15}A\right)} \tag{26}$$

$$B_6 = \mp\sqrt{\frac{2\mu_0}{S}\left(\frac{\sqrt{3}}{5}\hat{f}_x + \frac{1}{5}\hat{f}_y + \frac{2\sqrt{3}}{15}A\right)} \tag{27}$$

$$B_1 = \pm\sqrt{\frac{2\mu_0}{S}\left(\frac{2\sqrt{3}}{15}\hat{f}_x + \frac{4}{5}\hat{f}_y - \frac{2\sqrt{3}}{15}A\right)} \tag{28}$$

where

$$A = \sqrt{\hat{f}_x^2 - 3\hat{f}_y^2 + 4\sqrt{3}\hat{f}_x\hat{f}_y} \tag{29}$$

From equation (3), coil currents are calculated by multiplying equations (26), (27), (28) and $g_0/(\mu_0 N)$. In case of other ϕ, coil currents can be calculated, similarly.

In the actual operation, the quantity of coil currents should be calculated from the reference value $\hat{f}_x, \hat{f}_y$. To avoid this problem, coil currents are computed by the following simplified equation.

$$i_K = -1^{(K-1)} k f(\phi - (K-1)\pi/3)\sqrt{f} \tag{30}$$

where

$$k = \sqrt{\frac{4g_0^2}{5\sqrt{3}\mu_0 S N^2}} \tag{31}$$

$$f(\phi) = \begin{cases} \sqrt{\sqrt{13}\cos(\phi - \frac{2\pi}{3} + \alpha) - D_1} & 0 \leq \phi < 60^\circ \\ \sqrt{\sqrt{3}\sin(\phi) + \sqrt{-4\cos(2\phi) - 1}} & 60^\circ \leq \phi < 120^\circ \\ \sqrt{-\sqrt{13}\cos(\phi + \frac{2\pi}{3} - \alpha) - D_2} & 120^\circ \leq \phi < 180^\circ \\ 0 & 180^\circ \leq \phi < 360^\circ \end{cases} \tag{32}$$

$$D_1 = \sqrt{-4\cos(2\phi + \frac{2\pi}{3}) - 1} \tag{33}$$

$$D_2 = \sqrt{-4\cos(2\phi - \frac{2\pi}{3}) - 1} \tag{34}$$

$$\alpha = \tan^{-1}\frac{3\sqrt{3}}{5} \tag{35}$$

By computing $f(\phi)$ beforehand and stored, the quantity of computation can be reduced.

EXPERIMENTAL RESULTS

Experimental Setup

In order to confirm the proposed control method, simple experimental setup were made and tested. The experimental setup is shown in figure 7. The rotor is set vertically. A ball bearing is installed to support the x, y and z directions. Hence the rotor has two degree on freedom in the x and y directions. Two displacement sensors are installed to detect x and y directional displacement. DC motor is installed above the ball bearing to rotate the rotor.

The control system is shown in figure 8. Coil currents are calculated by DSP. Displacement signals from sensors are transformed into the DSP and calculated coil

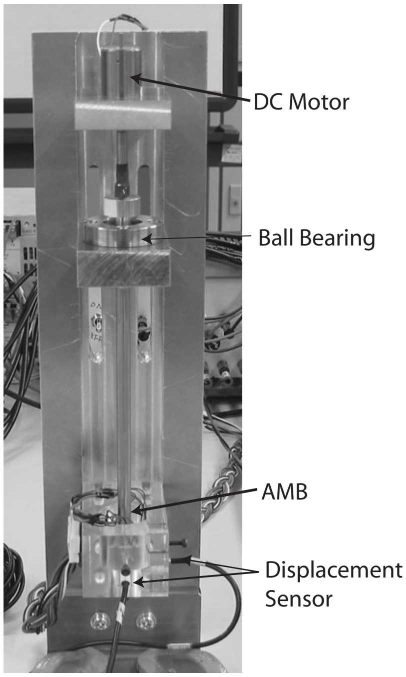


Figure 7: Experimental Setup

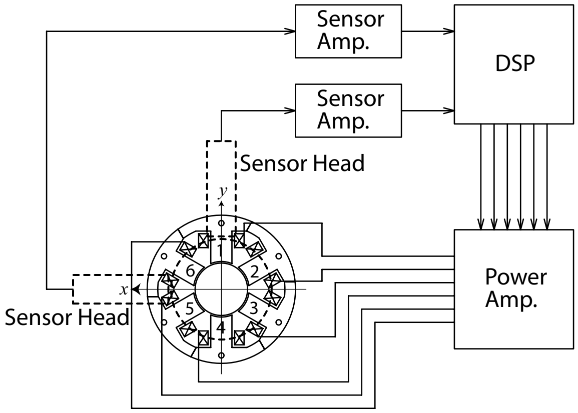
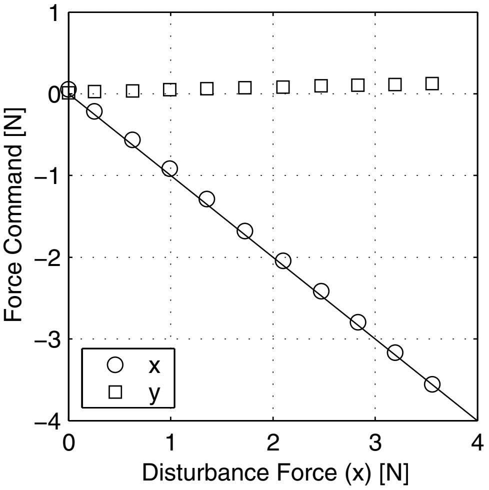


Figure 8: Control System

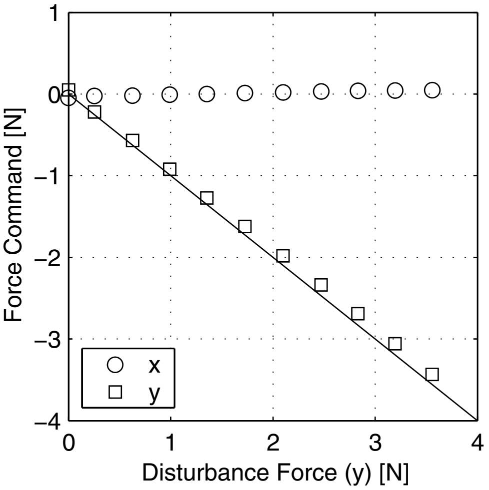
currents are fed to the stator coils through a six-channel current type power amplifiers.

Bearing Force

Figure 9 shows the results of measuremed the bearing force. These figures show the relationship between the force command and the actual bearing force. Figure 9 (a) shows the results of x direction and (b) shows those of y directions. In both cases, the bearing force is in proportion to the force command. These results show that the bearing force can be controlled independently by proposed control method.



(a) x direction



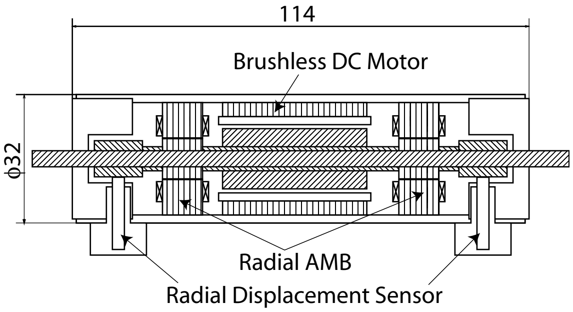
(b) y direction

Figure 9: Radial force

Furthermore, in case of zero disturbance force, both force commands $\hat{f}_x$ and $\hat{f}_y$ become zero. This results confirm the operation of the proposed minimum control.

PROTOTYPE MOTOR USING 6-POLE AMB

The prototype small motor using 6-pole miniature AMB is introduced. The schematic drawing and pictures of the prototype motor are shown in figure 10, 11 and 12. It is consists of two 6-pole AMB and brushless DC motor between them. In order to simplify the structure, the axial magnetic bearing does not fabricated. The outer diameter is only 32 mm and the total length is 114 mm. The prototype motor is now under testing. In the near future, we will show test results.



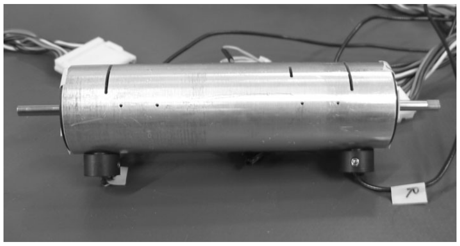


Figure 10: Prototype AMB motor

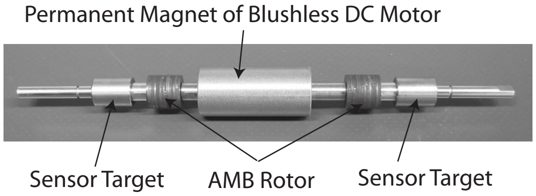


Figure 11: Rotor

CONCLUDING REMARKS

This paper introduces the design and control of a miniature active magnetic bearing. In order to balance the cost and bearing force, 6-pole active magnetic bearing is proposed. Then the minimum energy control method, which minimize the total copper loss in the stator, is introduced. The experimental results shows that the bearing force can be controlled by the proposed method. Finally, the prototype motor using proposed miniature active magnetic bearing is introduced. In the near future, we would introduce the test results.

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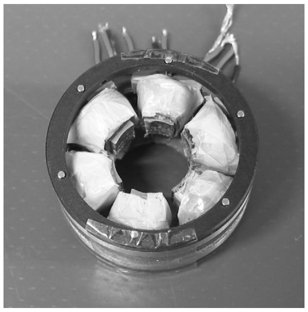

Figure 12: Stator