A Self-bearing Motor with a Passively Levitated Rotor

Ho-seong Kwak and Seung-Jong Kim
Tribology Research Center
Korea Institute of Science and Technology
39-1 Hawolgok, Sungbuk, Seoul, 136-791, Korea
sjongkim@kist.re.kr

***Abstract* – This paper proposes a passive self-bearing motor which combines two switched reluctance motors and a passive magnetic bearing(PMB) based on the repulsion between permanent magnets. Its structural feature is that the cores of the motor, which are attached on both sides of the PMB, are also utilized as flux paths for permanent magnets. For a strong levitation force, the permanent magnets of PMB are stacked like Halbach array, and for rotation, it works just like a switched reluctance motor. Compared with conventional self-bearing motors which are mostly based on the theory of active magnetic bearings, the proposed self-bearing motor has a very simple and small structure, and the production cost is very low. Through some FEM analysis results, the feasibility of the proposed motor was confirmed and the design parameters were determined.**

***Index Terms* – Self-bearing motor, Passive magnetic bearing, Switched reluctance motor, Halbach array, Repulsive force**

I. INTRODUCTION

Since the early 90's, many researchers have been interested in a self-bearing motor(or bearingless motor) that have combined characteristics of electrical motors and magnetic bearings, and various kinds of self-bearing motors have been developed. But, because most of them are based on the active magnetic bearing(AMB) theory, they require the expensive sensors and power amplifiers as well as a complicated control algorithm, even though they are compact, small and efficient[1~3]. This may be a drawback when the self-bearing motor is applied into a field that requires a less expensive and very simple self-bearing motor, allowing a vibration to some extent, such as a fan used in a clean room. The easiest way to develop such a self-bearing motor may be to substitute ball bearings of a motor with passive(or repulsive) magnetic bearings(PMB) using permanent magnets[4]. However, this reveals some problems such as low damping, weak force, and the necessity of covering the magnetic flux or avoiding the flux interference.

This paper proposes a new scheme for passive self-bearing motor(PSBM). Its structural feature is that since the motor cores are attached on both sides of the PMB, the cores are utilized as flux paths for PMB as well as for the motor windings, which helps to increase the levitation force and to design a small PSBM. For rotation, it works just like a conventional switched reluctance motor. As for the PMB, permanent magnets are stacked like Halbach array, which can increase the flux density in air gap between rotor and stator and reduce the flux going outward, resulting in an efficient PMB[5,6]. This PSBM has some good points such as inherently stable levitation, low production cost, and small structure. In addition, if necessary, low damping which is a typical weak point of PMBs can be improved by controlling the magnitudes of motor currents.

On the other hand, as well known, the instability in axial direction is inevitable in this configuration[7]. So a method to axially support the rotor, for example, 1-DOF AMB, should be devised. But this part is out of the scope of this paper. In this paper, we introduce the basic structure and operating principle in detail, and show some FEM analysis results to predict the performance of the proposed PSBM.

II. STRUCTURE AND ROTATION PRINCIPLE OF PSBM

A. Structure of the proposed PSBM

Fig.1 shows a schematic view of the proposed PSBM. Two sets of typical switched reluctance motor cores are symmetrically attached on the both sides of the stacked permanent magnets, and the cores of rotor and stator are designed to have 6 and 8 teeth, respectively. Each motor is independently driven. And as mentioned above, the cores also provide the flux paths to permanent magnets, which makes the reluctance low, resulting in increasing the flux

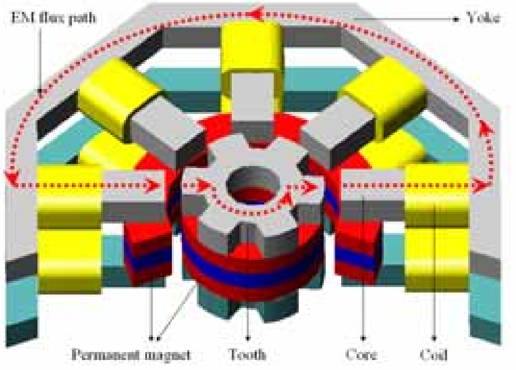
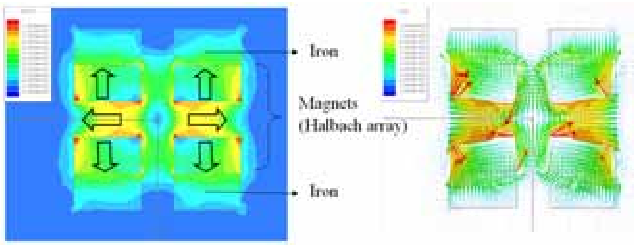
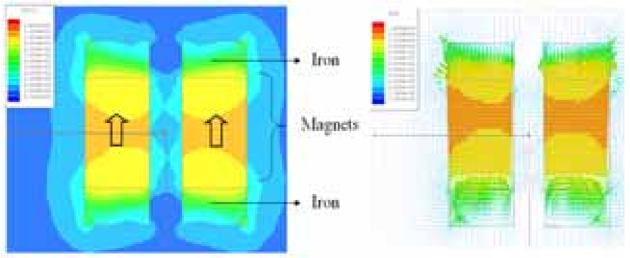


Fig. 1 Schematic view of the proposed PSBM



(a) Repulsion between two Halbach arrays with back yokes

⇦ ⇨ **Repulsive direction**



(b) Repulsion between two permanent magnets with back yorks

Fig. 2 Comparison of the flux flow patterns

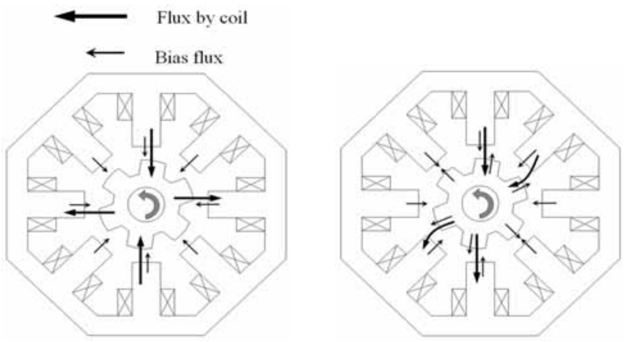
produced by permanent magnets. In addition, this structure can maximize the spatial utility, which leads to a small PSBM. On the other hand, the permanent magnet stack consists of three permanent magnet. The middle one is magnetized in radial direction, and the others are magnetized in axial direction as shown in Fig. 2(a).

Fig. 2 compares the flux flow patterns when two identical permanent magnets typically make the repulsive force and when the two stacks proposed in this paper push out each other. As expected, the former case makes much lower flux density in the air gap than the latter case, that is, Halbach array. And in Fig. 2(b), since the bulk of fluxes are pushed outside due to the repulsion, the flux passing through the air gap becomes smaller than the flux going outside. Meanwhile, such a phenomenon cannot be seen in Fig. 2(a), if any.

Here note that the flux density distribution in the yokes is quite partial, that is, the fluxes are concentrated near the permanent magnet(maximum flux density is about 0.9 T). From this, we can see that the thickness of the yoke is not so important for PMB, if it is not too thin.

B. Rotation Principle of PSBM

Fig. 3 explains the rotation principle of the PSBM, comparing with that of a conventional homopolar switched reluctance motor. In the case of Fig. 3(a), when all bias fluxes flow to the rotor across the air gap(homopolar), the 4-pole 2-phase winding is proper to drive the motor. If it generates the fluxes as shown in Fig. 3(a), these fluxes are added to, or subtracted from the bias flux, which results in a torque counter clockwise. On the other hand, in the air gap of the proposed PSBM, since all core faces have the same polarity so as to generate the repulsive force, we could use the above 4-pole 2-phase winding no longer. It is because in this case, the change of flux density has no concern with the direction of the coil flux. In other words, as shown in Fig.3(b), the resultant flux patterns in the upper and lower air gaps are the same with each other. Here, note that the coil flux decreases the repulsive force and further, if the coil flux becomes stronger than the bias flux, an attractive force can be produced in that air gap. Fig. 3(b) shows the rotation principle of the proposed PSBM, using 2-pole 4-phase winding. Actually this 2-pole 4-phase winding is often used for the conventional switched reluctance motor with 8 and 6 teeth in stator and rotor, respectively. Then, the rotor of the Fig.3(b) rotates counter clockwise, too.



(a) a homopolar stepping motor (b) the PSBM

Fig. 3 Rotation principles of (a) a homopolar stepping motor and (b) the PSBM

III. PERFORMANCE PREDICTION BY FEM ANALYSIS

A. Repulsive force

Fig. 4 shows the repulsive forces according to the size of air gap for the two cases shown in Fig. 2. For the air gap of 2 mm, the repulsive force of Fig. 2(a) is about twice as much as that of Fig. 2(b). And as the air gap becomes closer, the discrepancy increases because the former increases exponentially, while the latter grows linearly. In the following analysis of this paper, we use the air gap of 1.5 mm and the thickness of the stacked permanent magnets of 6 mm.

On the other hand, the permanent magnets consisting of the general Halbach array have the same square cross sections, but the permanent magnets in the stack of Fig. 2(a) does not. Thus, it needs to investigate proper thickness ratio of three permanent magnets to maximize the repulsive force. Fig. 5 shows the result, where one can see that the ratio of 1.7:2.6:1.7 produces the maximum repulsive force. But there is no distinct difference in the range between 1.9:2.2:1.9 and 1.5:3.0:1.5. Thus, it is judged to be reasonable to determine the ratio so that the thickness of middle magnet is 1/3 ~ 1/2 of total thickness.

Fig. 6 displays the relation between the thickness of cores(or yokes) attached on the both sides of permanent magnet stack and the repulsive force. Here, one can see that the core thickness is not concerned with the force as long as the flux saturation does not occur in core.

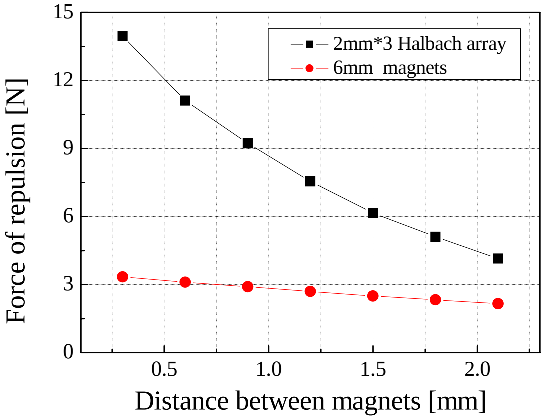


Fig. 4 Comparison of repulsive forces for the cases shown in Fig. 2

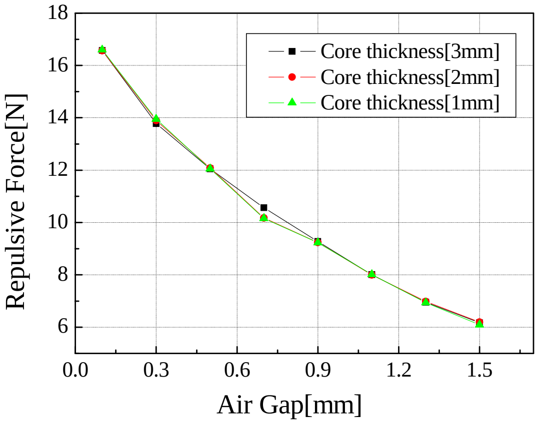


Fig. 6 Radial stiffness of the proposed PSBM

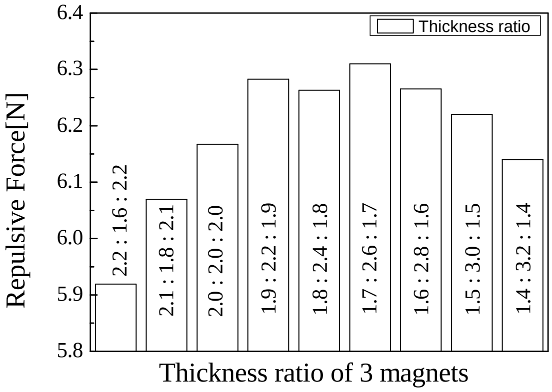


Fig. 5 Repulsive force vs. thickness ratio of permanent magnets

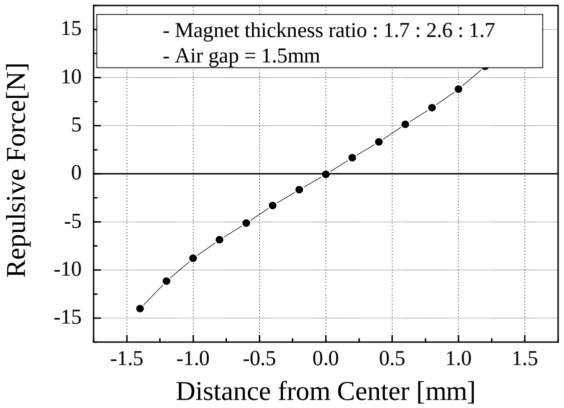


Fig. 7 Radial stiffness of the proposed PSBM

Referring to Fig. 2(a), if the yoke thickness is larger than about 0.5 mm, there is no flux saturation in this design. Thus, it can be determined in consideration of only the torque. We used the yoke thickness of 3 mm in the analysis.

Fig. 7 shows the relation of repulsive force and displacement of rotor, analysed with finally determined parameters, where the relation is quite linear except 10 ~ 20% section of both sides end and its slope means a radial stiffness of the designed PSBM. In the figure, the stiffness is about 8.8 N/mm

B. Torque

To carry out the torque analysis in the PSBM, three dimensional analysis is necessary, because it is needed to consider the fluxes by permanent magnets and coils, which flow in a plane parallel to the rotor axis and perpendicular to it at a time, respectively. Fig. 8 shows the constructed 3-D model of the designed PSBM.

Fig. 9 is the torque analysis results according to the rotation angle when only two opposite windings in a stator are live and provide the *magneto-motive force* of 800 A·turn which is the amount to theoretically create a flux density of about 0.67 T in the air gap. Line (a) in the figure corresponds to the case of Fig. 2(a), where the maximum torque is about 1.57 Nmm at the rotation angle of 12˚. The very small torque is judged to be caused by the large air gap and the thin core thickness. Nevertheless, the torque pattern is similar to that of the conventional stepping motor with a step of 15˚. The reason that maximum torque appears not at 15˚ but at 12˚ can be considered as: the flux densities produced by permanent magnets of stator and rotor are non-uniform over the core surfaces due to the repulsion effect between them. It means the bias flux density at each core surface varies according to the rotation

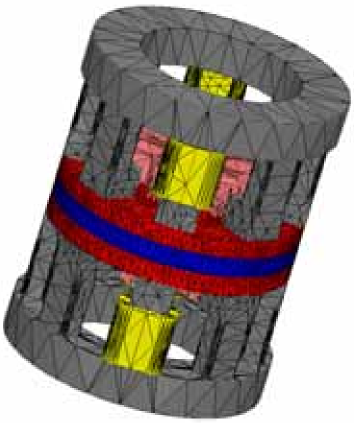


Fig. 8 The meshed 3-D model for FEM

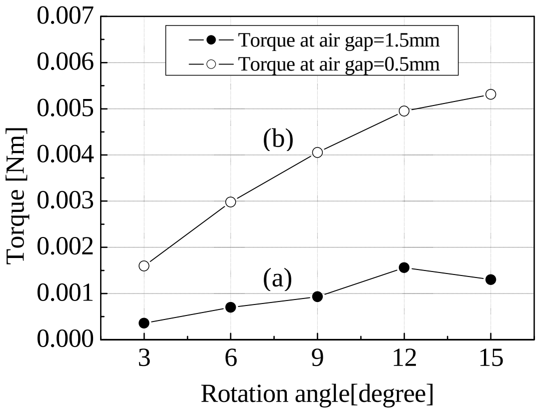


Fig. 9 Torque deviation according to the rotation angle

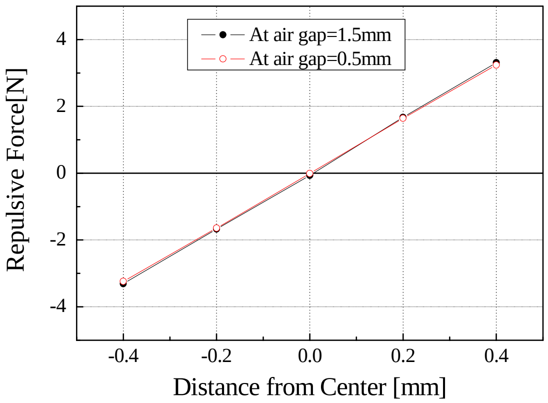


Fig. 11 Comparison of radial stiffness after modifying the core shape

angle, which leads to the torque deviation. In addition to that, the non-uniform air gap which is unavoidable in the real system may affect the torque, too. For reference, on stator core surface, the flux density produced by permanent magnets is calculated from maximum 0.76 T (corner that is near with permanent magnet) to minimum 0.04 T(far side corner).

To increase the torque, we modified the shape of core surface as shown in Fig. 10. That is, a step(height: 0.5 mm) was partially formed. This modification gives a merit that it can separate the flux paths at the core and increase the motor torque. Most of the coil flux across through the steps because of the narrow air gap, while the bias flux is concentrated in the part near the permanent magnets, which helps so as to simply design the switch reluctance motor. Fig. 11 shows how much this modification affects the repulsive force. After modified, the slope of the line(or bearing stiffness) negligibly decreases by about 2% (8.29 N/mm to 8.12 N/mm) in the range of -0.4 ~ +0.4 mm.

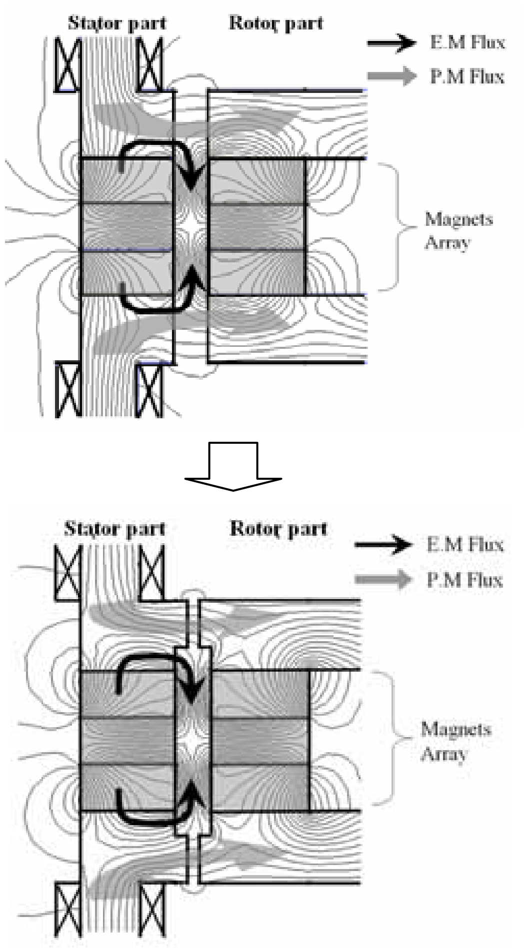


Fig. 10 Modified PSBM

Line (b) in Fig. 9 is the torque after the core is modified. As expected, it is significantly increased. Maximum torque was calculated by about 5.3 Nmm at the angular position of 15°.

On the other hand, the proposed PSBM should be actively controlled(or supported in contact) in at least one direction like other PMBs. Fig. 12 shows a conceptual figure including an axial AMB. This axial AMB gives a very good point in addition. The controllable axial displacement makes it possible to also change the natural frequency, because the levitation(repulsive) force depends on the relative axial displacement of stator and rotor. Thus, unlike other PMBs, the rotor in this PSMB can be speed up over the natural frequency without large vibration.

IV. CONCLUSIONS

In this paper, we proposed a PSBM that combines the switched reluctance motor and PMB. It has some advantages such as compact and simple structure, high stability, low production cost, and high reliability, compared with conventional active-type self-bearing motor. This PSBM can be applied into a rotary system that requires compact and inexpensive magnetic levitation, meanwhile, that high precision and high torque are not necessary, such as low noise cooling or fan in high clean room.

In system, the Halbach Array was very useful to increase the efficiency of PMB, and the cores attached on the PMB also contributed to the compactness of motor and high repulsive force.

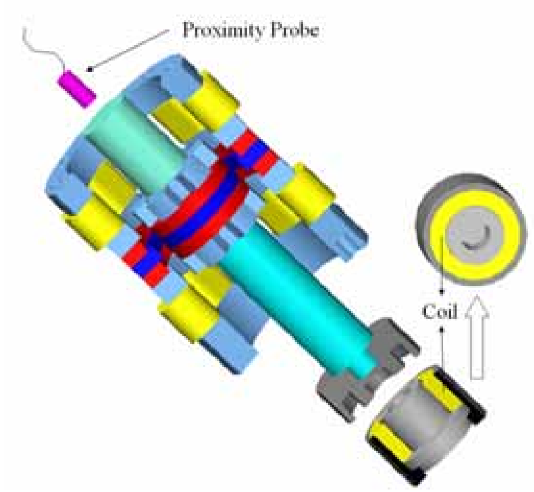


Fig. 12 Schematic view of the PSBM with an axial AMB

of motor. Through the FEM analysis, we could find a design scheme and simulate its performance such as levitation force and torque. As a result, we could get the stiffness coefficient of 8.8 N/mm and the maximum torque performance of 5.3 Nmm.

Including the axial AMB unit, a prototype of PSBM is going to be manufactured soon for experimental verification.

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