MiracBearing: NEW CONCEPT OF MIRACLE MAGNETIC BEARINGS

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ABSTRACT

A new and miracle magnetic bearing is proposed in this paper. It is intended for a magnetic bearings to have high efficiency, good dynamic response and low cost. Traditional magnetic bearing is composed of a pair of electromagnets which have strong non-linearity and require high level bias current. Hence the efficiency is not good or it requires narrow air gap. Hybrid type magnetic bearing is recognized as an efficient one. But the bias permanent magnet should be installed between the two radial magnetic bearings. It requires thick magnetic circuit and produces flux leakage. In this paper a new and smart magnetic bearing is proposed which is based on the hybrid type. The bias permanent magnets are installed inside the radial magnetic bearings. Hence all the magnetic circuit is closed inside the radial magnetic bearing and it is relatively free from the flux leakage. To confirm the proposed magnetic bearing, an experimental setup is designed and tested. The results showed high efficiency with relatively low control current.

INTRODUCTION

Active magnetic bearings (AMB) have been gradually used for high speed spindle or clean environment applications[(1),(2)]. Usually they have composed of the pair of electromagnets in push-pull operation which have strong non-linearity. Relatively high level bias current is used to linearize and to improve the dynamic property. Hence the efficiency is not good or it requires narrow air gap. Hybrid type magnetic bearing is recognized as an efficient one and having good dynamic property[(3)]. But the bias permanent magnet (PM) should be installed between the two radial magnetic bearings. This construction requires thick magnetic circuit between them which causes heavy structure. The flux leakage from the bias PM causes several problems or it restricts the application.

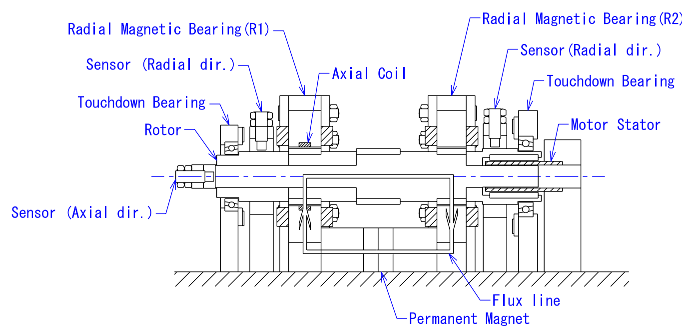

FIGURE 1: Schematic of HB AMB

In this paper a new and smart magnetic bearing is proposed which is based on the hybrid type[(4)]. The bias PMs are installed inside the radial magnetic bearings. Hence all the magnetic circuit is closed inside the radial magnetic bearing and it is relatively free from the flux leakage. This new magnetic bearing (MiracBearing) is suitable for relatively small size and wide air gap AMB applications. The fundamental concept of this new magnetic bearings is introduced. To confirm the fundamental operation of the proposed magnetic bearing, two types of proposed AMBs are analyzed using the finite element code ANSYS. An educational version of four pole type with four PM sub-slots was designed and fabricated. The fundamental characteristics were tested. The results showed high efficiency with relatively low control current. It also showed good dynamic prop-

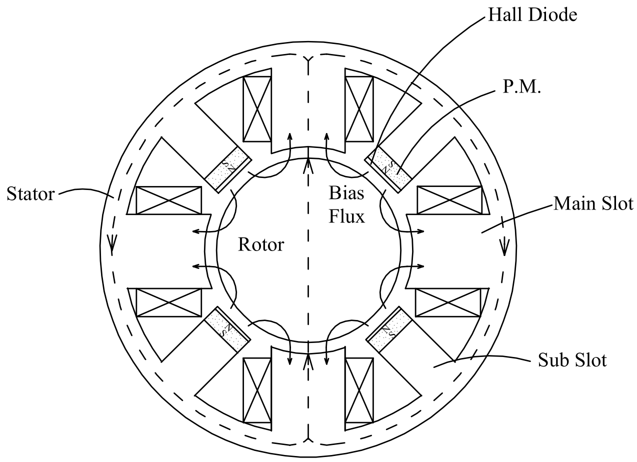

FIGURE 2: Schematic of Proposed 4-Pole AMB

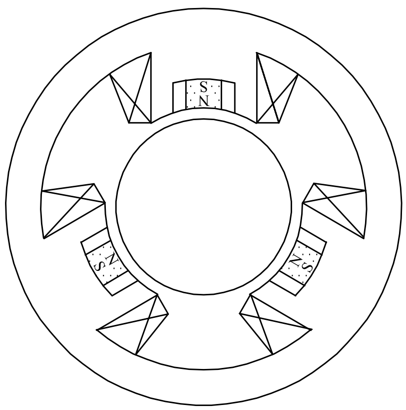

FIGURE 3: Schematic of Proposed 3-Pole AMB

erties and stable operation. Finally possibility of new self-sensing technique using Hall diode is introduced. Integration of axial magnetic bearing in radial magnetic bearing is also introduced.

INTERNAL PM TYPE HYBRID MAGNETIC BEARINGS

A typical hybrid AMB is shown in Fig. 1 [(3)]. Hybrid AMB is recognized as an efficient one. But it requires thick magnetic circuit and apt to produce flux leakage. A new and miracle magnetic bearing (MiracBearing) is proposed in this section.

Structure and Principle

An example of the proposed magnetic bearing is shown in Fig. 2. It has four main poles with control windings. Four sub poles have strong PMs which are installed between the main poles. These PMs produce the bias magnetic flux as shown by the

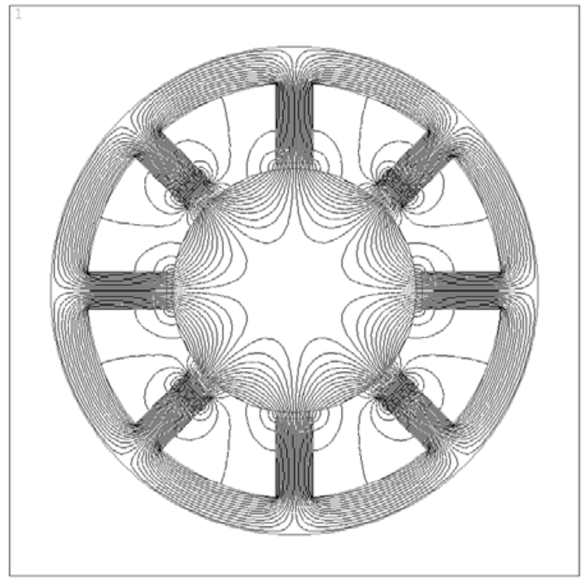

FIGURE 4: Flux Line of 4-Pole AMB

arrow lines. The pair of main poles have windings which are connected series. The control current in these coils produce the control flux as shown by the dashed arrow lines. Figure 2 shows the case where the upper flux is increased and the lower flux is decreased. Hence the upward force is produced by the control current.

The standard hybrid AMB shown in Fig. 1 has the drawback of long bias flux path and apt to cause flux leakage. On the contrary the bias flux path of the proposed AMB is closed inside the radial AMB. Hence it has merits of short flux path and relatively free from flux leakage. This type of AMB is easily applicable to the small spindle or wide air gap application because of high efficiency.

Another example of three pole type is shown in Fig. 3. In this case the bias PMs are installed inside the main slots, hence it is easily applicable to the small spindles. Three pole type can be controlled by the three phase motor control power amplifiers.

The bias flux from the stator PMs should go to the rotor and then come back to the stator. If the bias flux leaks from PMs to the stator directly, the control force is not effectively produced or it has nonlinear characteristics. For this purpose the distance between the main pole and sub pole is selected more than twice of the air gap in Fig. 2. In the case of Fig. 3 the ditches between the PM and the stator are introduced to avoid the direct bypass of the bias flux.

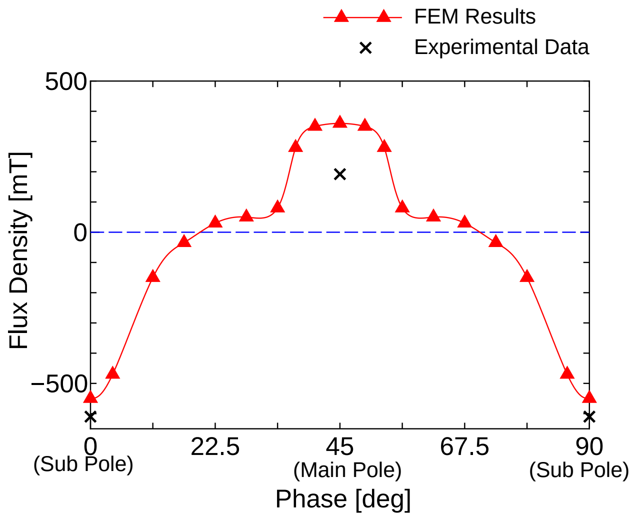

FIGURE 5: Flux Density Distribution

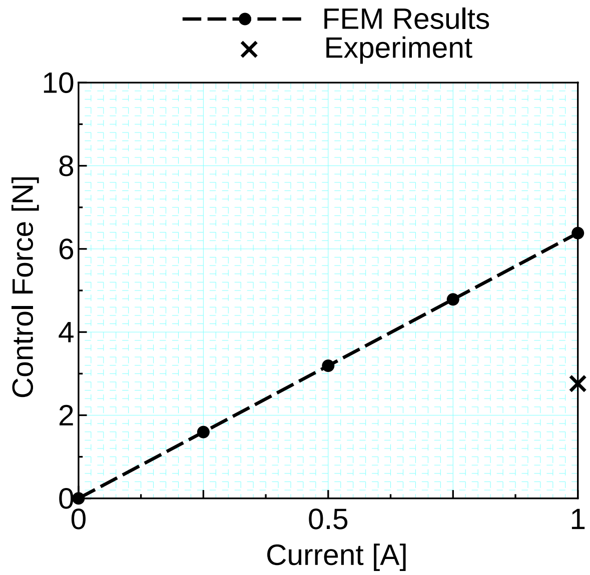

FIGURE 6: Control Force of 4-Pole AMB

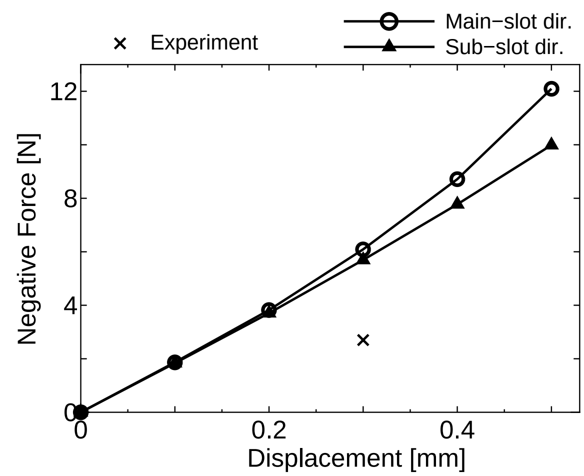

FIGURE 7: Negative Stiffness of 4-Pole AMB

FEM ANALYSIS

To confirm the operation of the proposed magnetic bearing finite element analysis of magnetic fields is carried out with the aid of ANSYS package.

Four Main Poles with Sub Poles

First the fundamental structure of four pole type AMB is analyzed. The calculated bias flux lines are shown in Fig. 4. The bias flux is well produced in the main poles. The air gap between the main pole and rotor is 1 mm while the air gap at the sub pole is 2 mm.

The flux density distribution is shown in Fig. 5. The flux density at the main pole is lower than that of the sub pole mainly due to the flux expansion. The flux density 360 mT of the main pole is considered good level for bias flux.

The control force and the negative stiffness of this AMB is also calculated as shown in Figs. 6 and 7, respectively. From these calculations the proposed AMB is predicted to control the rotor levitation well.

PM Included Three Pole Type

For a small AMB system the pole number is better to be small. PM included three pole type is analyzed and its flux flow line is shown in Fig. 8. The bias flux is well produced. The control force and negative stiffness are also calculated as shown in Figs. 9 and 10, respectively. However, these forces are nonlinear. Even though the levitation is able to be controlled. In this calculation the air gap of 1 mm is used. To improve the force characteristics narrow air gap will be recommended, hence it is suitable for small AMB.

EDUCATIONAL PURPOSE AMB SYSTEM

An experimental setup is made aiming to the mechatronics education, which is schematically shown in Fig. 11. Two aluminum angles are set parallel to make channel form base. Under which power amplifiers PA-12 are installed with the power supply (±24 V, 2 A max.). The developed AMB is installed left side on the base. Touch down bearing, two eddy current type sensors (2.5 V/mm) are installed near the AMB. The right side of the rotor shaft is supported

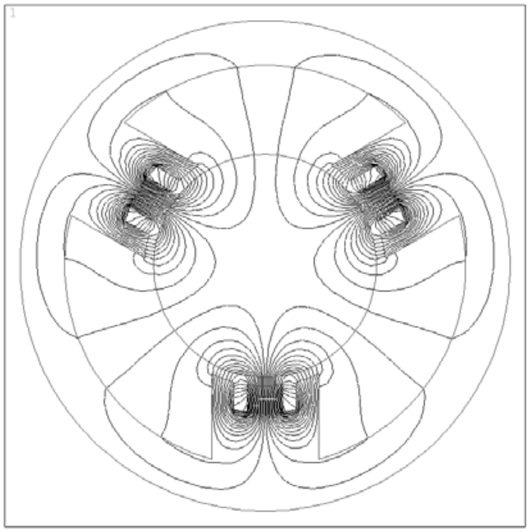

FIGURE 8: Flux Line of 3-Pole AMB

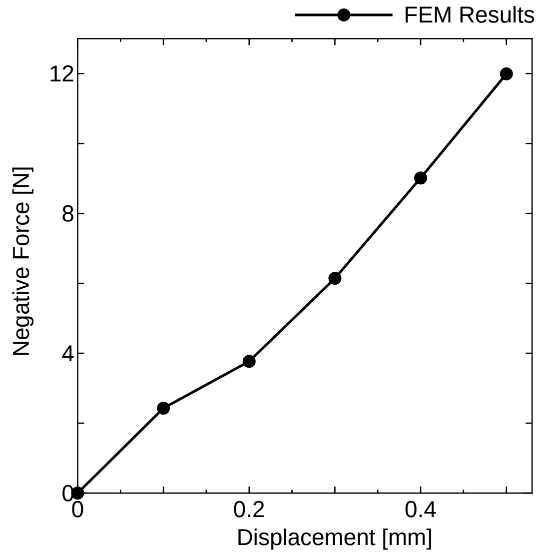

FIGURE 10: Negative Stiffness of 3-Pole AMB

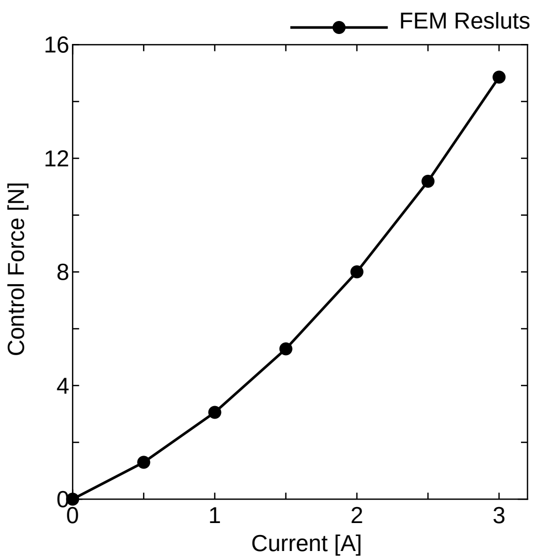

FIGURE 9: Control Force of 3-Pole AMB

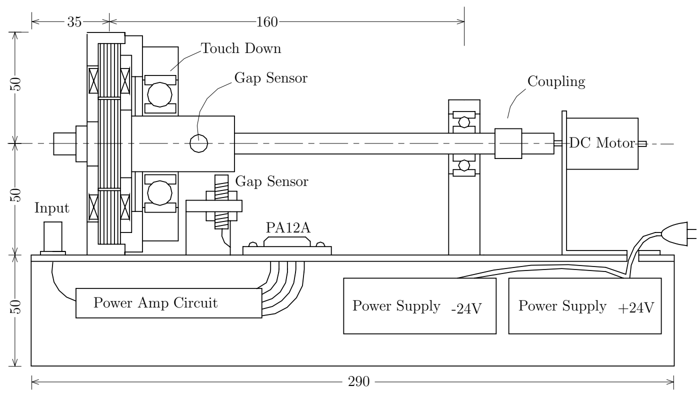

FIGURE 11: Experimental Setup

by a ball bearing, hence the rotor has two radial degrees of freedom. DC motor is attached to drive the rotor through rubber coupling. The total weight of the rotor is 0.435 kg and the equivalent weight at the bearing point is 0.35 kg. Compared with the AMB size the rotor is relatively heavy. The controller used is digital PID installed in dSPACE (DS-1102).

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To confirm the capability of the proposed AMB system, experiments are carried out.

Static Characteristics

First, the air gap flux was measured. The results are shown by the × marks in Fig. 5. At the sub pole the measured flux of −610 mT was bigger than the calculated one of −550 mT. This is considered due to the manufacturing error. On the contrary the measured flux at the main pole of 192 mT was far smaller than the calculated value of 360 mT. The analysis is based on 2 dimensional FEM. However, the actual flux will flow three dimensionally. The experimental setup has backup bearing near the AMB which will increase the leakage flux. Hence one should carefully design this type of AMB to avoid the flux leakage between the rotor and the stator. The touch down and the sensor target are better to be made of non-magnetic materials.

The measured control force recorded 2.76 N at the control current of 1 A which is shown by × in

TABLE 1: PID Controller

	x-dir.	y-dir.	unit
K_p	20	40	V/V
K_d	0.025	0.05	V/V s
K_i	0.0005	0.001	V s/V
T_d	1	1	ms
τ	0.1	0.1	ms

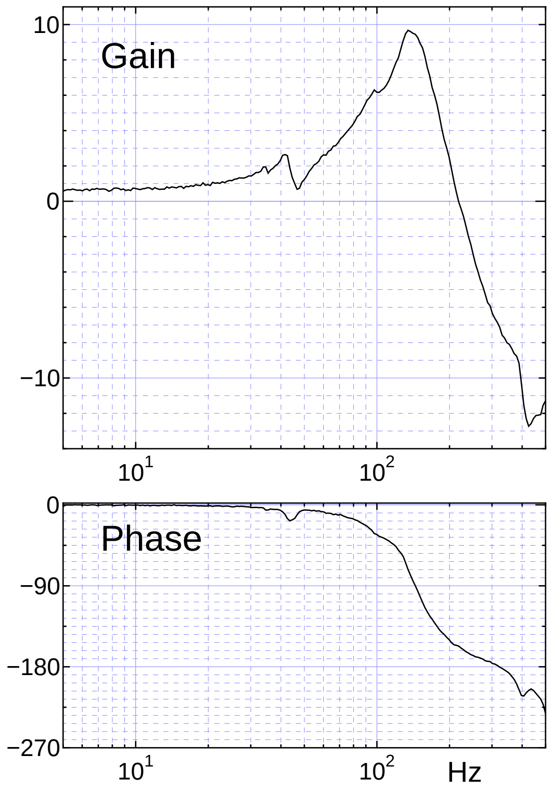

FIGURE 12: Frequency Response: x-direction

Fig. 6. Also the measured negative force was 2.7 N at the rotor displacement of 0.3 mm which is shown by × in Fig. 7. Both forces were smaller than the calculated results. This is also considered due to the bias flux leakage of the designed AMB.

Dynamic Characteristics

The rotor could be levitated stably using the digital PID controller, the parameters of which are shown in Table 1. The vertical gains in y-direction were twice bigger than the horizontal gains in x-direction, respectively. This is due to the heavy weight of the rotor. The vertical amplifier needed the static levitation current about 1.5 A.

The frequency responses for x- and y-directions are shown in Figs. 12 and 13, respectively. They

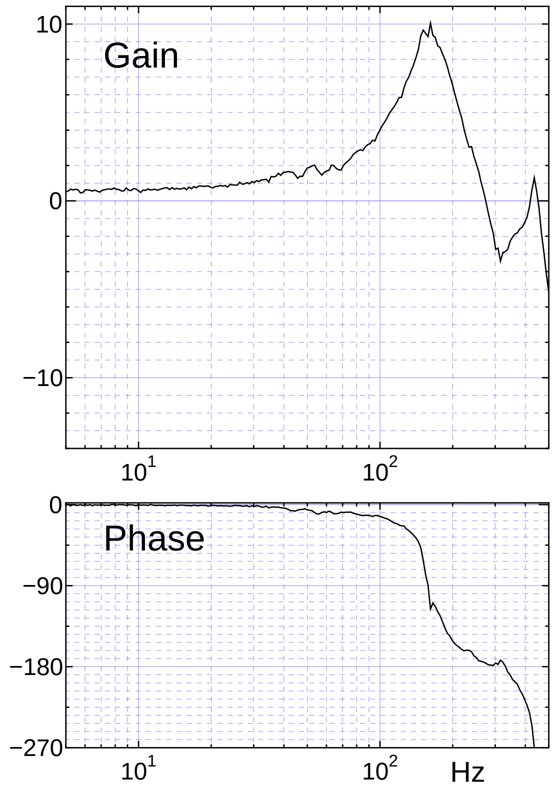

FIGURE 13: Frequency Response: y-direction

were measured by adding the sinusoidal signal to the sensor feedback point and measuring the corresponding displacement. The peaks at about 150 Hz were slightly high, but the levitation was stable. The transient response could not be measured because of the small margin of the maximum power amplifier current of 1.8 A.

Levitated Rotation

The rotor could run smoothly up to 2,500 rpm by adding the current to the DC motor. The measured unbalance responses are shown in Fig. 14. However, the rotor touched down over 2,800 rpm due to the lack of AMB power margin. The experimental setup is now under modification to improve the stability of levitation.

UTILIZING TOP OF SUB POLE

New functions are introduced which utilize the top of sub pole. One technique proposed is the self-sensing using the flux sensor which is schematically shown in Fig. 2. The designed AMB shown in Fig. 4 has wider air gap of 2 mm at the sub pole while that at the main pole is 1 mm. The Hall diode can

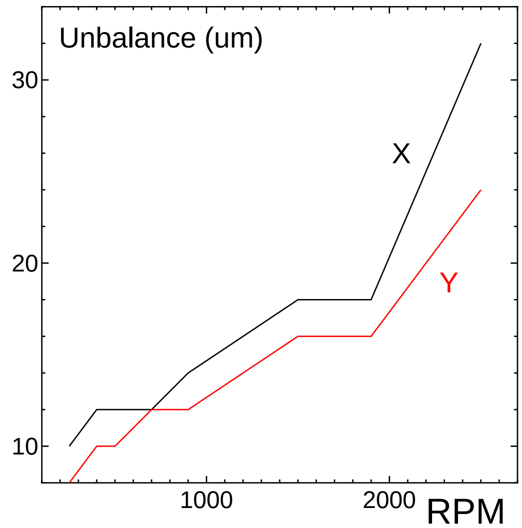

FIGURE 14: Unbalance Response

be installed in this extra air gap to measure the bias flux change. The flux is considered inversely proportional to the gap displacement. Two Hall sensors are used in the opposite gap and the difference of the two Hall sensor signals is used to measure the rotor displacement. Hence the linearity and signal to noise ratio can be improved.

Another idea is the integrated axial AMB. Fig. 15 shows scheme of this idea. In this case the bias PMs are installed outer side of the sub poles. On the bias PM, magnetic core with axial control winding is installed. The cross section is shown in the lower graph of Fig. 15. This magnetic core is designed wider than that of rotor core. The current of the axial coil increases the upper bias flux and decreases the lower bias flux. These fluxes have axial components. Hence the flux difference produces the upward force to the rotor. There are four axial control cores in the sub pole surfaces, hence three dimensions can be controlled: one axial and two tilt directions. Only one radial magnetic bearing has the capability of controlling 5 active control degrees.

CONCLUDING REMARKS

A miracle magnetic bearing is proposed which is expected to have high efficiency, good dynamic response and low cost. An educational version of experimental setup was designed. The results showed relatively good dynamic characteristics compared to the small size. However the power was not enough and the system is now under modification. Further

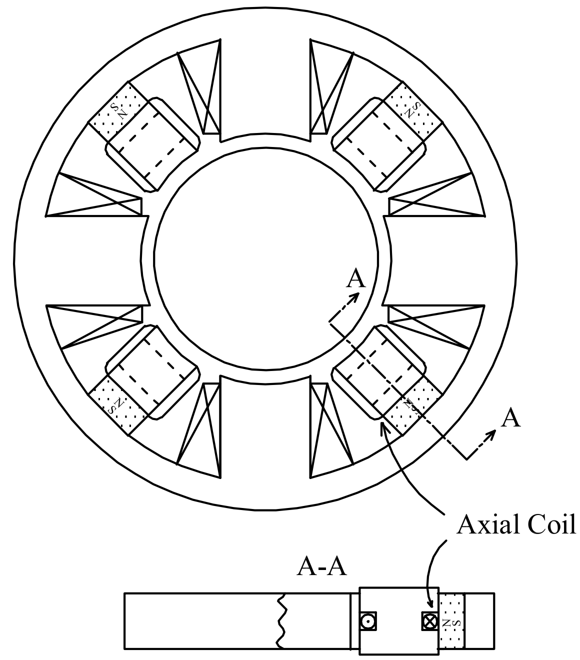

FIGURE 15: Schematic of 5 Axes Control AMB

work is continuing to develop both bigger and smaller experimental setup and apply them to the real machines.

References

1. Y. Okada, et. al., JSME Publication on New Technology Series, No. 1, Magnetic Bearings - Fundamental Characteristics, Design and Applications, Yokendo Ltd., Tokyo, 1995, in Japanese (translated into Korean)
2. S. Ueno, et. al., Development of Miniature Magnetic Bearing for Small Motor, Proc. of 15th Symp. on Electromagnetics and Dynamics, 2003, pp. 609-612, in Japanese
3. N. Kurita, Y. Okada and K. Matsuda, Development of Lossless Magnetic Bearing, Proc. of 8th Int. Symp. on Magnetic Bearings, Mito, August 26-28, 2002, pp. 91-96
4. Y. Okada, H. Koyanagi and S. Ueno, Development of Internal PM type Hybrid Magnetic Bearings, Proc. of 8th Symposium on Motion and Vibration Control, Tokyo, Oct. 30-Nov. 1, pp. 186-189, in Japanese