DEVELOPMENT OF LOSSLESS MAGNETIC BEARING

Nobuyuki Kurita
Dept. of Mechanical Eng., Ibaraki University, Hitachi, Ibaraki-Pref., 316-8511 Japan
hkurita@mech.ibaraki.ac.jp
Yohji Okada
Dept. of Mechanical Eng., Ibaraki University, Hitachi, Ibaraki-Pref., 316-8511 Japan
okada@mech.ibaraki.ac.jp
Ken-ich Matsuda
Dept. of Mechanical Eng., Ibaraki University, Hitachi, Ibaraki-Pref., 316-8511 Japan
matsu@mech.ibaraki.ac.jp

ABSTRACT

For high speed and long term rotor such as an energy storage flywheel, eddy current in the laminated steel sheet causes rotating loss. In this paper, new type of magnetic bearing is proposed which has the smooth flux distribution. The rotating loss is expected to be negligible, while it has high force factor due to the high bias flux produced by permanent magnets. To confirm the operation of the proposed magnetic bearing, a simple experiment was fabricated and tested. The results demonstrate smooth rotation with a low vibration level. It can run up to 15,600 rpm without any problem.

INTRODUCTION

Electric power requirement increases in daytime while the night power remains in the low level. The electric power plants are better to operate constantly. The efficiency of electric power plants will be improved, if the power is stored efficiency. The pump power storage system is widely used; that is the water is pumped up to higher dam by the surplus electric power in night, while the electric power is generated from the water potential energy in daytime. But it is not highly efficient due to the pumping and generating loss and their long distance from a big city. An energy storage flywheel is expected as one of the most efficient methods [1]-[3]. The flywheel is accelerated by electric motor at night using surplus power while it generates the electric power in daytime. Hence such a flywheel should pass the critical speed and keeps high-speed rotation between night and daytime. This requires for the magnetic bearing to suppress the critical vibrations and to have very low rotating loss. Several types of energy storage flywheel have been developed and reported recently [4].

The magnetic bearing is usually considered without any rotating loss. However such a high speed and long-term application, eddy current loss in thin steel sheet causes serious problem. This paper proposes a new type of magnetic bearing which produces almost zero eddy current loss. Standard magnetic bearing has the concentrated pole stems which are magnetized N or S poles alternatively. Eddy current is induced in the rotor when it rotates in such a sudden flux change. The proposed magnetic bearing is based on the hybrid type one which has high bias flux produced by permanent magnets. The stems have long foot between them to smooth the flux distribution. Control flux is relatively low level. Hence the flux distribution is smooth in the rotating circumference to avoid the eddy current. The proposed magnetic bearing is designed using the finite element code ANSYS. The designed results show smooth flux distribution. Even the control flux is low level, this magnetic bearing produces the required bearing force. The designed magnetic bearing is fabricated with the axial magnetic bearing and AC motor. The same size of standard magnetic bearing is also made for comparison. They are tested to confirm the validity of the proposed magnetic bearings. A new axial magnetic bearing is developed which uses Lorentz force. This is arranged in the middle of two radial magnetic bearings. Strong permanent magnets are sandwiched between the axial and radial magnetic bearings which

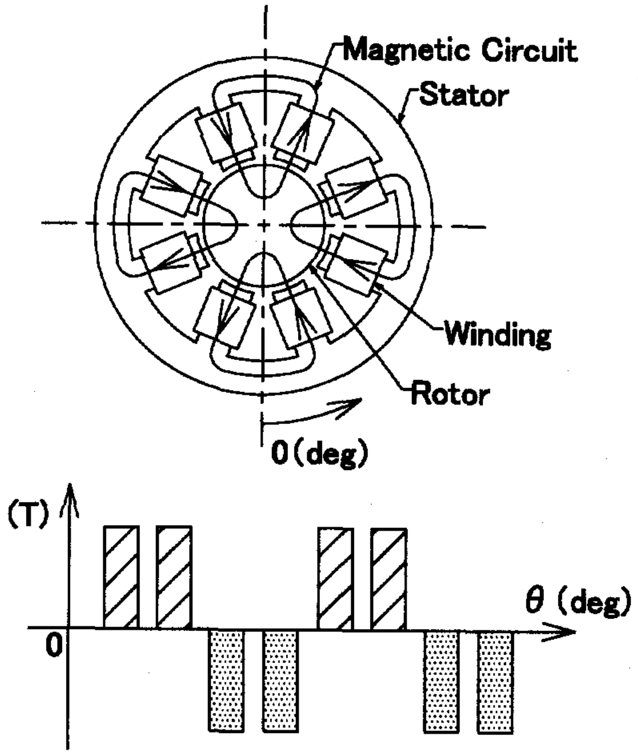

FIGURE 1: Schematic of Standard Magnetic Bearing

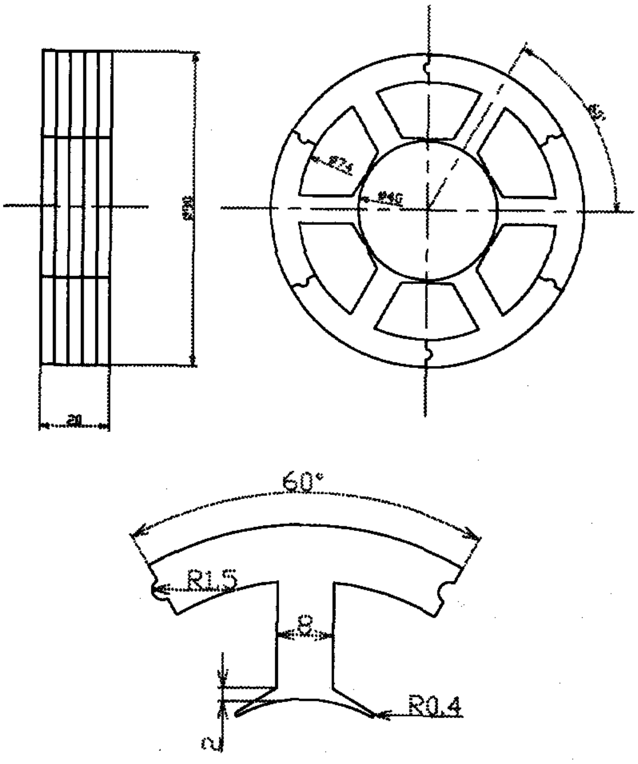

FIGURE 2: Schematic of Stator

supply the bias flux. Hence the efficiency is very good. A PM type high-speed motor/generator is mounted on the right end. They can give the rotating torque for acceleration. The experimental rotating rest is carried out and the results show very smooth rotation.

LOSSLESS MAGNETIC BEARINGS

The schematic of the standard magnetic bearing is shown in Fig. 1. The flux density distribution in the airgap is shown in the lower part of Fig. 1. The poles are magnetized N and S alternatively. The rotor rotates across this flux, hence eddy current is produced in the rotor causing rotational loss. For the usual rotating speed application, this problem can be overcome by using a laminated steel sheet. However for high speed and long-term rotor such as energy storage flywheel, the rotating loss is a serious problem.

Operation of The Proposed Magnetic Bearing

The structure of the proposed magnetic bearing is shown in Fig. 2. This is based on a Hybrid type, but the leg has foot to smooth the flux distribution. The magnetic flux in the foot is expected to saturate with the bias flux, hence the control flux is not flow into the neighboring foot. The stator is designed using the magnetic field analysis "ANSYS". The calculated result is shown in Fig. 3. The bias flux flows in the airgap between the rotor and stator. Where smooth flux distribution is recognized. Operation of the proposed magnetic bearing is shown in Fig. 4 that is the same of Hybrid type magnetic bearing. One side of the flux is increased while the other side flux is decreased by the control current. However the flux distribution along the gap circumference is designed to have sinusoidal form.

Bearing Force

The flux density generated by the electromagnet current of i=1[A] is given by eq. (1) [5]. The parameters used in this calculation are listed in Table 1. A dummy rotor was made and used to allow the space for Hall sensor for flux measurement. The airgap is

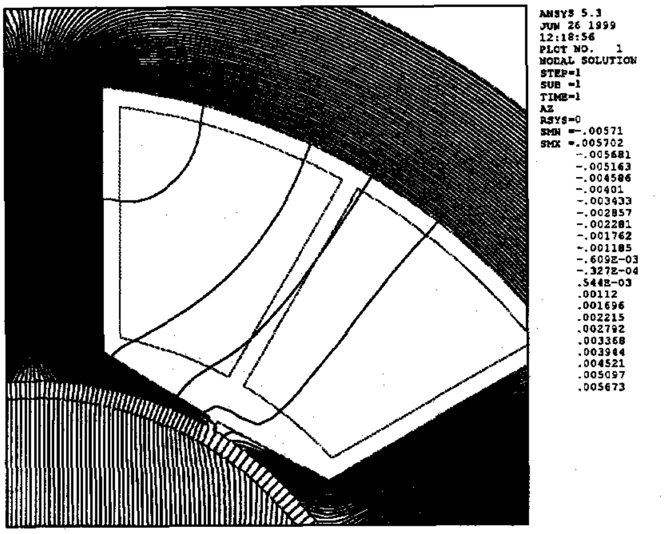

FIGURE 3: Result of Magnetic Flux Analysis

2.25[mm]. The flux density is calculated by

$$\begin{aligned} B_e &= \frac{\mu_0 N}{(l/\mu_s) + 2g} \times i \\ &= \frac{4\pi \times 10^{-7} \times 540}{200 \times 10^{-3}/8000 + 2 \times 2.25 \times 10^{-3}} \times 1 \\ &= 0.149963 \qquad (1) \end{aligned}$$

To smooth the flux, foot is attached to each leg, which has larger area. The flux value needs to consider the area ratio of leg to foot and the leakage flux into the next foot. Therefore, the actual flux density is estimated as follows.

$$\begin{aligned} B_e &= 0.149963 \times \frac{8}{(\frac{40}{6}\pi)} \times \frac{15}{19} \\ &= 0.045222 \qquad (2) \end{aligned}$$

The bearing force is calculated from the flux of eq. (2) and the measured bias flux density of the permanent magnet $B_p = 140[mT]$. The cross-sectional area is $S = 40\pi/6 \times 20 \times 10^{-6} = 4.14 \times 10^{-4}[m^2]$. Then we have the force for one leg as,

$$\begin{aligned} F &= \frac{\{(B_p + B_e)^2 - (B_p - B_e)^2\}S}{2\mu_0} \\ &= \frac{B_p B_e 2S}{\mu_0} \\ &= \frac{0.045222 \times 0.14 \times 2 \times 4.14 \times 10^{-4}}{4\pi \times 10^{-7}} \\ &= 4.222 \qquad (3) \end{aligned}$$

The total bearing force is obtained by the summation of each stems about x and y-direction.

$$F = 6.332 \ [N] \qquad (4)$$

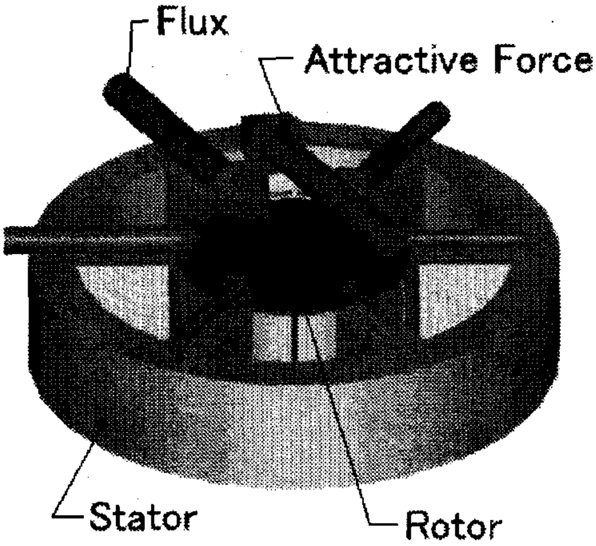

FIGURE 4: Operation of Radial Magnetic Bearing

TABLE 1: Parameters of Radial Magnetic Bearing

Turns of Winding	N	=	540	[Turns]
Length of Magnetic Path	l	=	200	[mm]
Airgap	g	=	2.25	[mm]
Control Current	i	=	1	[A]

The measured flux density distribution is shown in Fig. 5. The values are relatively well agreed with the calculated ones. The attractive force inversely proportional to the square of the airgap. Since the actual airgap is designed as 1 [mm]. The following force is assumed to be produce at the current of i=1[A].

$$F = 32.06 \ [N] \qquad (5)$$

This value is enough for controlling the rotor.

Axial Magnetic Bearings

The attractive force of the radial magnetic bearing stabilizes the axial motion passively, but the damping is poor causing serious problem for high-speed rotation. To overcome this problem an axial magnetic bearing is designed which is based on Lorentz force principle.

The operational principle of an axial magnetic bearing is shown in Fig. 6. The bias flux flows uniformly from the stator to the rotor. The coil is wound around the inner circumference and fixed to the stator. The coil current produces Lorentz force based on a Flemming's law. Since the coil is fixed to the stator, the reaction force acts on the rotor. This force

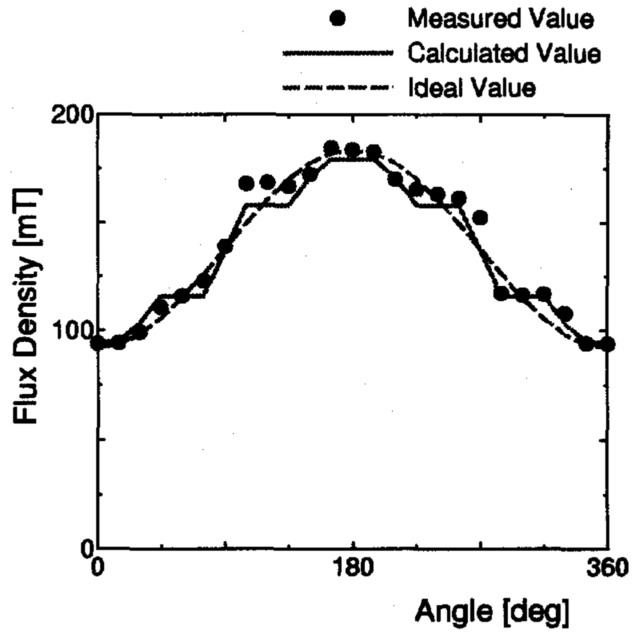

FIGURE 5: Flux Density of the Proposed Magnetic Bearing

is used for axial direction bearing control.

$$F = BlI \tag{6}$$

where, B is the bias flux density, l is effective length of coil and I is control current. The measured flux density is 140 [mT] and the total length of coil is 25.126 [m]. Therefore, the Lorentz force is given by,

$$\begin{aligned} F &= BlI \\ &= 0.14 \times 25.126 \times I \\ &= 3.52 \times I[N] \end{aligned} \tag{7}$$

This force is not strong enough to control the axial position but enough to increase the rotor damping.

EXPERIMENT

In order to confirm the basic operation of the proposed magnetic bearing, the experimental setup is made as shown in Fig. 7.

Experimental Setup

The rotor is set horizontally and the proposed magnetic bearing is arranged on both ends. Moving magnet type brushless DC motor provides the rotational torque which is installed at the right end. The axial magnetic bearing is installed in the center of the rotor. The permanent magnet is sandwiched between the axial magnetic bearing and the two radial magnetic bearings. The bias flux path is shown by the thick dotted lines in Fig. 7. The airgap in the radial direction is 1[mm] while that of axial bearing is 4 [mm] including the coil winding. The touchdown bearings are installed to avoid direct contact. Hence the movable area is decreased to 0.5[mm] in the radial and axial directions. Bearing control used is a digital PID controller. The control gains are determined experimentally and are listed in Table 2, where K_p is the proportional gain, K_d is the derivative gain, and K_i is the integral gain. The sampling interval τ is 0.1[ms] and the derivative time constant T_d is 0.3[ms]. The radial bearing on the free side is abbreviated as "R1" while the motor side bearing is indicated as "R2". The axial bearing is also abbreviated as "Axial".

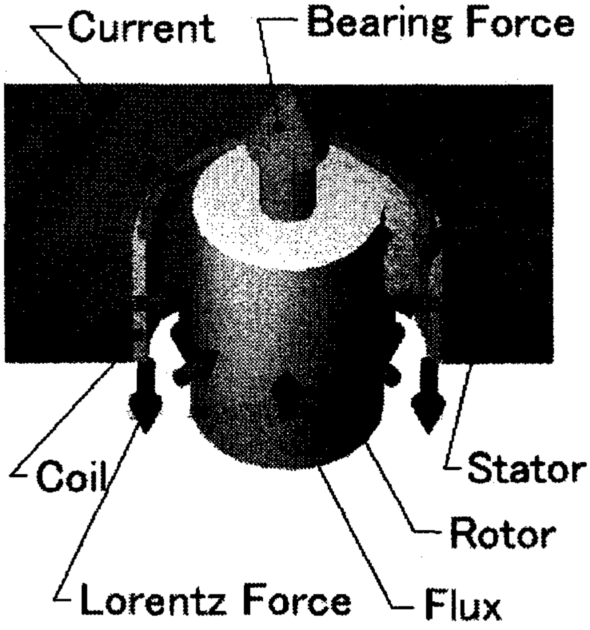

FIGURE 6: Operation of Axial Magnetic Bearing

TABLE 2: Control Parameters

Item	Unit	R1	R2	Axial
K_p	$[A/mm]$	7	8	10
K_d	$[A \cdot sec/mm]$	0.022	0.03	0.03
K_i	$[A/sec]$	2	2	3

Frequency Response

The frequency response of the proposed magnetic bearing is measured using an FFT analyzer. A sinusoidal signal of ±0.05[V] was put into the power

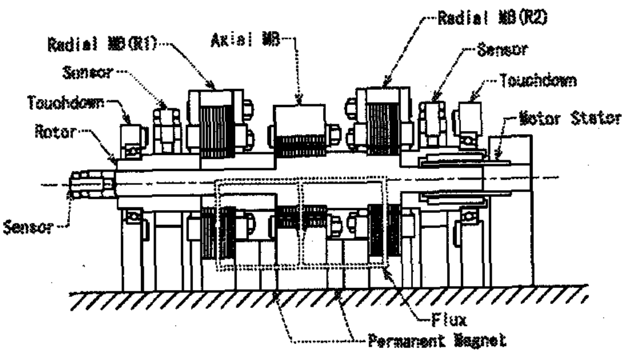

FIGURE 7: Schematic of the Proposed Magnetic Bearing System

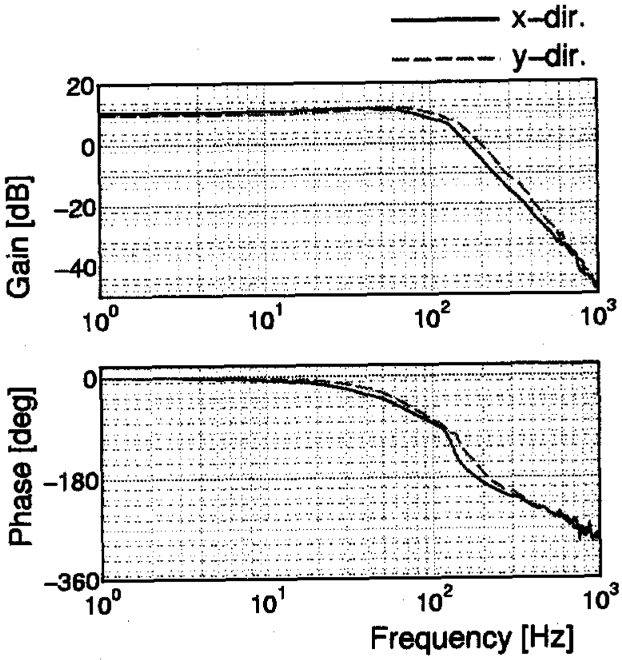

FIGURE 8: Frequency Response of Free Side (R1)

amplifier from the frequency of 1[Hz] to 1000[Hz]. The measured results of x and y radial directions of R1 are shown in Fig. 8. The first peak is about 90 [Hz] which is considered to be the rigid body mode. Since the peak is suppressed, bearing control performance is good. The results in x and y direction are mutually almost equal.

Impulse Response

Impulse response was measured by hammering the rotor end about 0.1 [mm] and recording the decaying vibration. The impulse response of the free end is shown in Figs. 9 and 10. The x and y directional vibrations are stabilized within 0.1 [sec]. There was almost no interaction between the x and y directions. Similar experiment was conducted on the axial direction as shown in Fig. 11. The vibration in this case is decayed approximately 0.3 [sec].

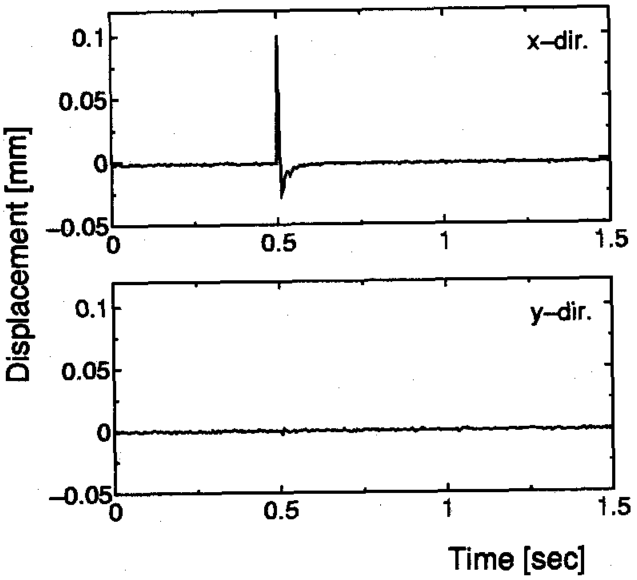

FIGURE 9: Impulse Response of X-direction

Levitated Rotation

The levitated rotating test is carried out. The unbalanced response is shown in Fig. 12. The rotating speed is increased 200[rpm] stepwise. After the rotor has reached to the steady-state speed, the vibration amplitude of peak to peak is measured and recorded in Fig. 12. Maximum unbalance is recognized at the speed of 5,500[rpm]. The amplitude of the rotor is controlled under ±0.02[mm] for all the measured rotating speed. The rotor could run up to 15,600[rpm] without serious problem.

FUTURE WORK

The proposed magnetic bearing showed very stable levitation and strong bearing force with relatively wide airgap. These properties are very good for the usual application. However we need to confirm the rotating loss. For this purpose we designed thc same size of standard magnetic bearing as shown in Fig. 13. We will compare the rotating loss between them in the vacuum chamber.

CONCLUDING REMARKS

New type of magnetic bearing is proposed to reduce the rotating loss. A test rig is fabricated and its

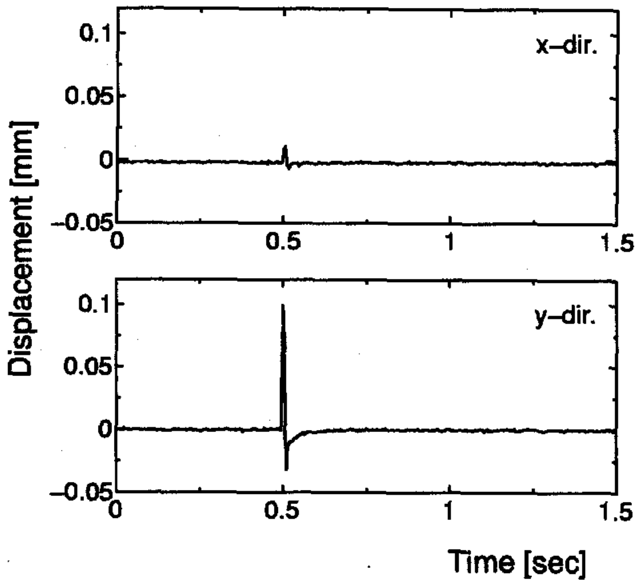

FIGURE 10: Impulse Response of Y-direction

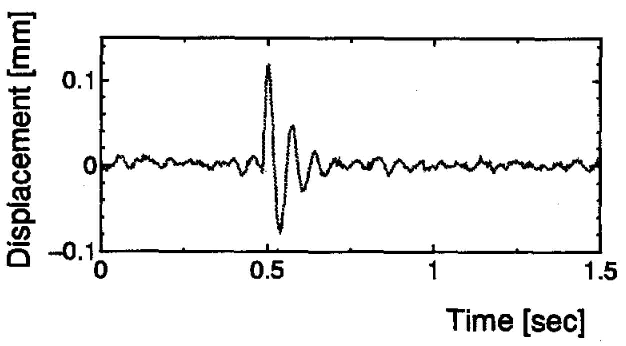

FIGURE 11: Impulse Response of Axial direction

fundamental characteristics are measured. The results show very stable levitation, low level vibration and strong bearing force with relatively wide airgap. These characteristics are very good not only for energy storage flywheel but also for the usual AMB application. Further work is continuing to clarify the rotating loss and to develop the actual applications including the turbo pump.

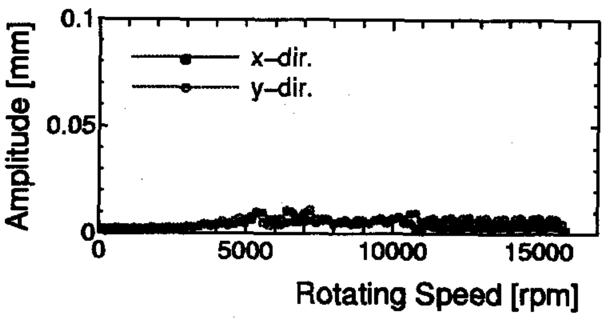

FIGURE 12: Unbalance Response

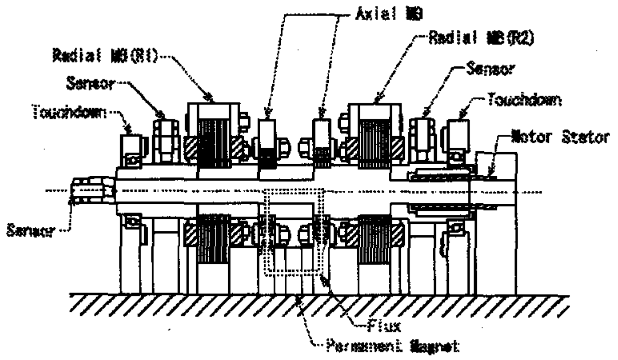

FIGURE 13: Schematic of the Standard Magnetic Bearing System

References

1. Markus Ahrens, et. al.,: "Design of a Magnetically Suspended Flywheel Energy Storage Device", 4th ISMB, ETH Zurich, 1994, pp.553–558.

2. H. Higasa, et. al.,: "Development of Super Conducting Magnetic Bearing with High Levitating Force for Flywheel Energy Storage System", IEEE Trans., on Applied Superconductivity, 1996, Vol.12 No.2, pp.662–625.

3. Y.Miyagawa, et. al.,: "A Trial Manufacturing of Flywheel Energy Storage System", Preprint of Applied Superconductivity Conference, 1998.

4. Saitoh, et. al.,: "Development of 10kWh Flywheel Energy Storage System", 12th Symposium on Electromagnetics and Dynamics, Naha, Okinawa, Japan, 2000, pp.371–375. (in Japanese)

5. Okada, et. al.,: "The Foundation and Application of Magnetic Bearings", Yoken-do. (in Japanese)