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Investigation of Configuration of Permanent Magnets on Repulsive Type Magnetic Bearing

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Abstract: As the magnetic bearing system has many electromagnets and controlled circuits, the problem of complicated control system and its high costs are incurred. In case the magnetic bearing is used for inertial energy storage under small radial disturbance, it is possible to simplify the radial control by using repulsive force of permanent magnets. The system can be applied to the uninterrupted power supply and flywheel energy storage. We have developed a new non-contact magnetic bearing system with the necessary controlled elements[2]. The stability of the overall system is very much influenced by the characteristics of the permanent magnets. This paper investigates the characteristics of permanent magnets and its configuration in Repulsive Type Magnetic Bearing system. It proposes the placement of the permanent magnets requiring no radial control resulting better stability of the total magnetic bearing system.

1 Introduction

Magnetic Bearing due to its non-contact nature does not produce noise and sound and has less vibrations compared to its counter part mechanical bearing. As it does not require any kind of lubrications, it can be used in different stringent atmosphere such as vacuum, clean room etc. In spite of its above advantages it has few drawbacks also. It needs electromagnets or a combination of electromagnets and permanent magnets and complicated control circuit for stability. In an active magnetic bearing system both thrust and radial controls are achieved perfectly but it needs lots of electromagnets in different directions which incur cost. In order to overcome the above problem and also to simply the control scheme, in this scheme the thrust has only been controlled by the controlled current electromagnet and the radial control by permanent magnet resulting a magnetic bearing system equal to that of original one. Utilizing the repulsive forces of permanent magnets for radial control, a model has been developed and experimented successfully in our laboratory[2]. This system can be used as a back-up energy storage such as fly-wheel and uninterrupted power supply.

As this type of magnetic bearing system is very much influenced by the characteristics of the permanent magnet, the knowledge of the permanent magnet characteristics is very much important to know beforehand in order to make a useful magnetic bearing system. This paper investigates the structure and configuration of the permanent magnets so that it results in better radial stability in the repulsive type magnetic bearing system. Using the results of above investigations one new model of magnetic bearing has been fabricated and developed. In this paper the modeling of the bearing system and its control system formulation has been discussed. The controller has been configured around a digital signal processor and the experimental results are also given.

2 Outline of Repulsive Type Magnetic Bearing System

2.1 Configuration of previous system

The previous model of permanent magnet repulsive type magnetic bearing system developed in this laboratory is shown in fig.1.

The rotor has two axially magnetized permanent magnet placed at two ends. The stator has also two permanent

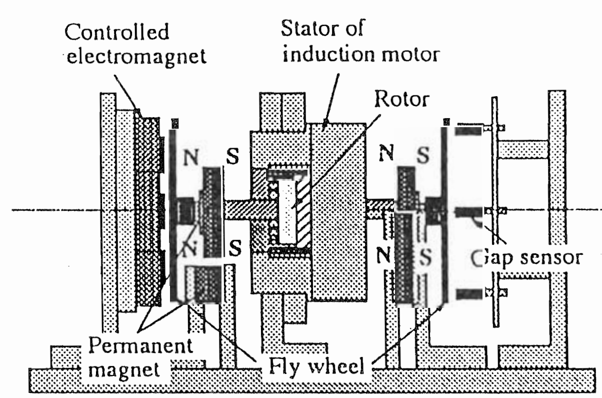


Fig.1 Configuration of the previous magnetic bearing system

magnet having the same magnetization axis as that of rotor and placed under the rotor permanent magnet. Using the repulsive forces acting between the stator and rotor permanent magnets the radial stability has been achieved. The system is unstable in nature in the axial direction. Using the controlled current electromagnet the system is made stable resulting a non-contact type magnetic bearing system.

2.2 Configuration of Permanent Magnet and Characteristics of Repulsive Forces

For making the new type of magnetic bearing, the nature and magnitudes of the repulsive forces acting between the stator and rotor permanent magnets of the configuration shown in fig.2 has been measured. By positioning the rotor magnets with respect to stator magnets the forces and stiffnesses along the three directions has been measured experimentally. The important characteristics parameters of the permanent magnets of both the previous model and a new configuration has been listed in table 1. Both the stator and rotor permanent magnet of the previous model are made of Sr-Ferrite but in the new model in order to have large repulsive force the stator magnet is made of Nd-Fe-B magnet and the rotor magnet is made of Sr-Ferrite. By placing the upper stator magnet as shown in fig.2, the forces and stiffnesses of this configuration are compared to that of without upper stator magnet.

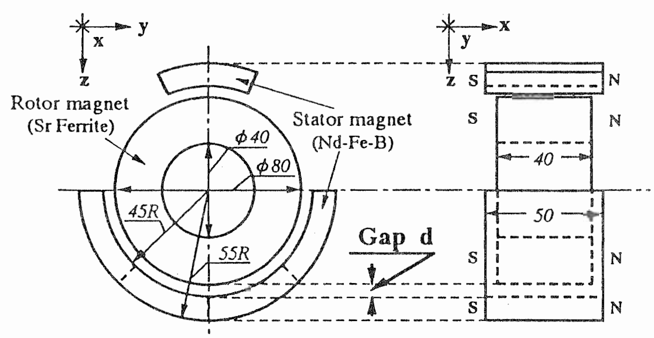


Fig.2 Configuration of permanent magnets

Table 1 Specifications of permanent magnet

Model	present	previous
Permanent magnet rotor stator	 Sr-Ferrite Nd-Fe-B	 Sr-Ferrite Sr-Ferrite
Coercive force Hc Sr-Ferrite Nd-Fe-B	 2.39×10^{5} A/m 1.07×10^{6} A/m	

The variation of repulsive force along z-axis, f_z with the gap for different values of x are shown in fig.3 both with and without upper stator permanent magnet. The variation of f_x (force along x-axis) with x-axis distance and f_y (force along y-axis) with y-axis distance for different values of d are shown in figs.6 and 4 respectively. The variation of stiffnesses along y-axis and z-axis with and without upper stator magnet is shown in figs.5(a) and 5(b) respectively.
From fig.3 it is seen that the repulsive force with upper stator permanent magnet is less compared to that of without one. It is seen that for x=2 mm and d=4mm, the repulsive for experienced without upper stator magnet is around 6 kgf but when the upper stator magnet is used it is reduced to 4 kgf i.e., 67% of the original value.
Fig. 4 shows that the repulsive forces with and without upper stator magnet varies only a little.
It is seen from fig.5(b) that stiffness with upper stator magnet is more than that of without upper stator magnet.
Fig.5(a) shows that stiffness along y-axis with upper stator magnet is slightly less than that of without one.
Considering the operating point x=1mm and d=4mm, the stiffness along z-axis with upper stator magnet is 1.8 times to that of without one which helps to improve stability of the system. From the results obtained from figs.3 to 5, this magnetic bearing system has been developed.
The attractive force to be produced by the electromagnet at the operating point is obtained from fig.6. The stiffnesses along x-axis are linear for both configurations. The repulsive force along x-axis at the operating point is 1.2 kgf when the upper stator magnet is used. From the above results the design parameters at the operating point is shown in table 2.

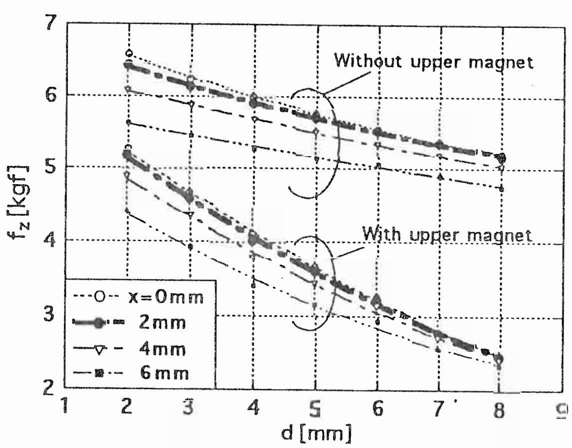


Fig.3 Variation of repulsive force with gap

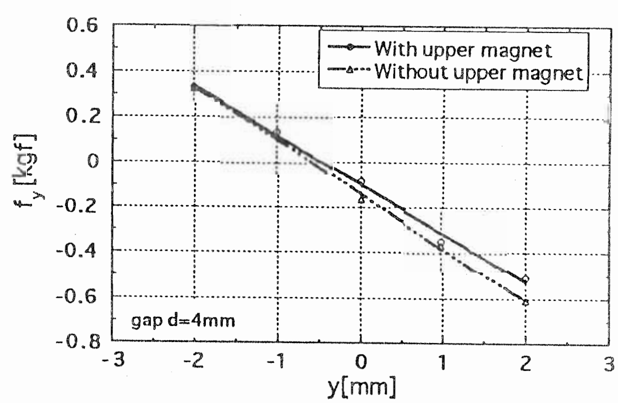
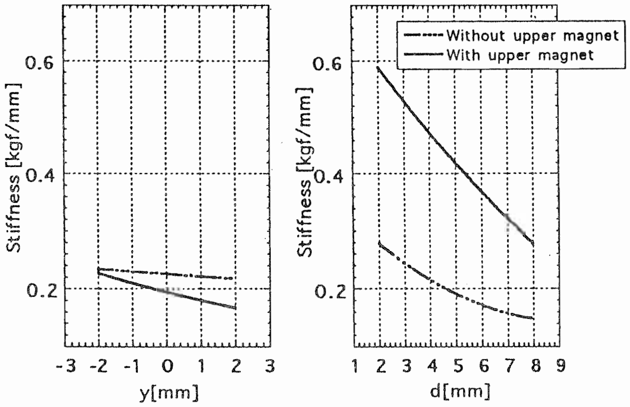


Fig.4 Variation of repulsive force with Y-axis distance



(a) Along Y-axis (b) Along Z-axis

Fig.5 Stiffness characteristic

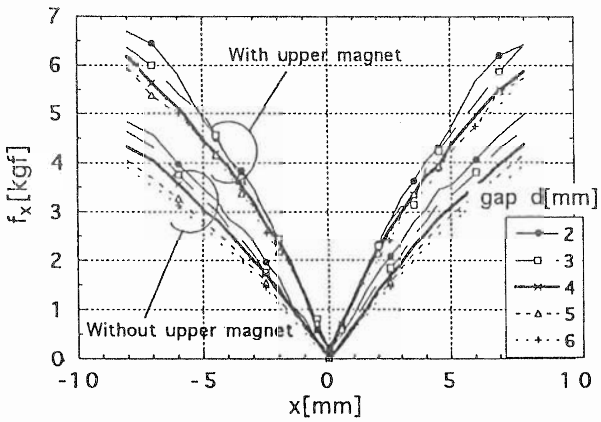


Fig.6 Variation of repulsive force with X-axis distance

Table 2 Design parameters

Operating point	d=4mm , x=1mm , y=0mm
Repulsive force	fz≒4kgf fx≒1.2kgf

3 Finite Element Analysis of Repulsive Forces

As the working of repulsive type permanent magnet bearing system is very much dependent on the permanent magnet characteristics, the knowledge of PM characteristic is essential. The present configuration is not symmetrical if 3-dimensional view is concerned. Considering the movement of rotor with respect to stator configuration the model can be reduced to a 2-dimensional one for the analysis to be made possible to avoid the complexity of 3-dimensional one. Using the 2-dimensional model the repulsive forces are calculated from finite element analysis.

The sectional view of fig.2 has been shown in fig.7 for 2-dimensional finite element analysis. A span of 180 along the surface has been divided into 18 equal parts each of 10 and the magnetic field is analyzed. By changing the rotor magnet positions with stator magnet as fixed one, the repulsive forces f_{rw}, f_{ru}, f_{su} and f_{sw} as shown in fig.7 are calculated. Total 19 such calculations are made. By adding all the vector forces acting along y and z axis, the total forces are calculated. This method of calculation forms a 2-dimensional analysis data base which helps to understand easily the repulsive forces with the rotor movement. The repulsive forces along y and z axis are calculated from the data base and are shown in figs.8(a) and 8(b) respectively. The calculated force characteristics of figs.8(a) and 8(b) when compared with the experimental values are look alike. From the calculated values also it is seen that in presence of upper stator magnet the stability improves. To be true this analysis neglects the edge effect which may introduce some error.

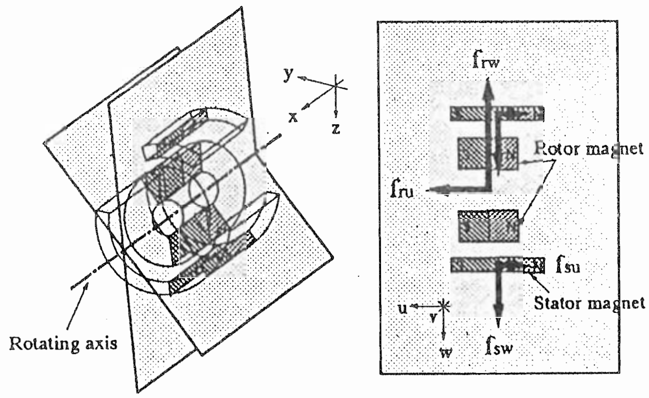
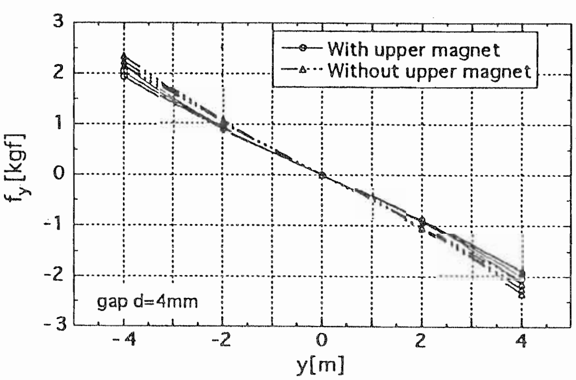
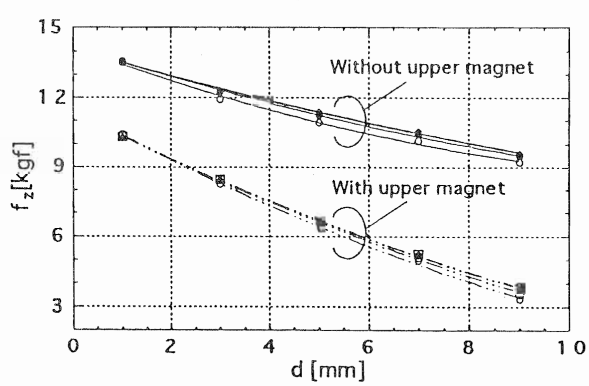


Fig.7 Sectional view of the magnet structure



(a) Along Y-axis



(b) Along Z-axis

Fig.8 Calculated repulsive force characteristic

4 Configuration of Repulsive Type Magnetic Bearing System

Using the design parameters listed in table 2, the present system shown in fig.9 has been developed. The total weight of the rotor (including magnets and rotating part of the rotor) is 8 kg. The rotor acting as flywheel is placed in the middle of the two rotor magnets resulting symmetrical arrangement which reduces the tendency of tilting along y and z axis. A sets of four electromagnets placed in the middle near the flywheel to keep it in the stable position by changing its current with the help of controller. Gap sensor placed in the opposite side to that of electromagnets has been used to measure the gap between the electromagnet and the rotor. At stable position the current of the electromagnet is set so that a force of 2.4 kgf is produced to keep the rotor at the desired stable point. The important parameters are listed in table 3.

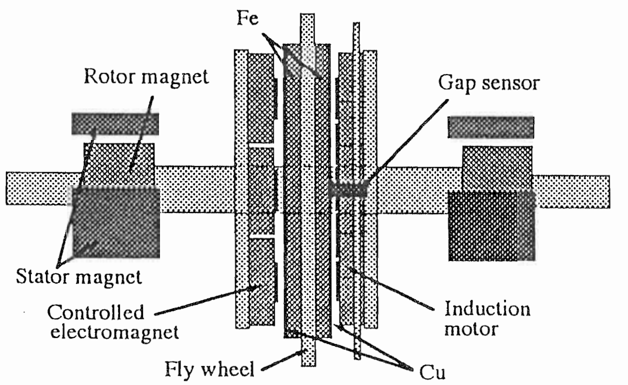


Fig.9 Configuration of new magnetic bearing system

Table 3 Parameters of rotor

Parameter	Symbol	Value	Unit
Mass of rotor,	m	8.0	kg
Inertia moment	Jx	2.379×10^{-2}	$kg \cdot m^2$
	Jy	8.364×10^{-2}	$kg \cdot m^2$
Radius of fly-wheel	ra	1.15×10^{-1}	m
Length of shaft	Le	5.1×10^{-1}	m

4.1 System Modeling and Control [3]

During modeling of the rotor few assumptions are made like (a) rotor is a rigid body dynamics and (b) rotor maintains symmetricity around the rotating axis. The forces acting on the rotor are shown in fig. 10.

The forces experienced by the permanent magnets in the x, y and z directions as shown in figs. 3, 4 and 6 are expressed by approximate equations as shown below.

$$f_a = Q/g_a \qquad (a = l_z, r_z) \qquad (1)$$

$$f_b = -Rg_b \qquad (b = l_y, r_y) \qquad (2)$$

$$f_c = Sg_c - 2F \qquad (c = l_x, r_x) \qquad (3)$$

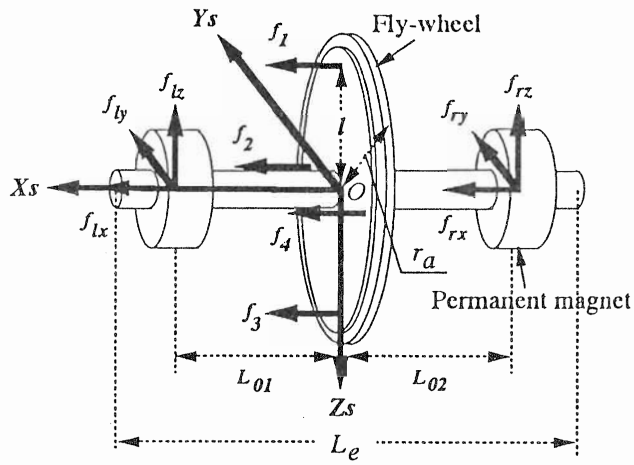


Fig.10 Modeling of rotor

For the formulation of the electromagnets the following assumptions are made.

(a) The force produced by the electromagnet is proportional to the square of current and inversely proportional to the square of gap distance.

(b) All the electromagnets are of identical structure.

(c) Deviation around the nominal operating point is small.

Linearizing the operating characteristic of the permanent magnet as well as electromagnet around the nominal operating point[2] and using the voltage equations of the electromagnet with the deviated quantities, the state space equations are obtained in matrix form as shown below.

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix} = \begin{bmatrix} 0 & I & 0 \\ B_1C_4 + B_2C_2 & A_1 & B_2C_3 \\ 0 & 0 & -L^{-1}RI \end{bmatrix}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ L^{-1}I \end{bmatrix} e \qquad (4)$$

$$y = \begin{bmatrix} C_1 & 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix} \qquad (5)$$

The above equations in (4) and (5) is the detailed equations for controlling pitch, yaw and axial displacement. In this system only one gap sensor has been used and all the electromagnets are not controlled separately, the system equations reduced to as shown below.

$$\frac{d}{dt}\begin{bmatrix} x' \\ \dot{x}' \\ i' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{2S}{m} + \frac{2}{mW}\sum_i F_i & 0 & \frac{2}{nI}\sum_i F_i \\ 0 & 0 & -\frac{r}{L} \end{bmatrix}\begin{bmatrix} x' \\ \dot{x}' \\ i' \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} e' \qquad (6)$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x' \\ \dot{x}' \\ i' \end{bmatrix} \qquad (7)$$

The parameters used in the model is explained below.

- x' : Gap derivation from nominal state
- i' : Current derivation of electromagnet from nominal state
- e' : Incremental input voltage to electromagnet
- m : Mass of rotor
- F_i : Attractive force at steady state
- I : Nominal current
- W : Nominal gap
- r : Resistance of electromagnet
- L : Inductance of electromagnet
- R,S : Constant used in permanent magnet eqation

Using the DSP as the controller, the block diagram representation of the control system is shown in fig. 11. The inputs to the controller are the gap displacement, its derivative and the current of the electromagnet.

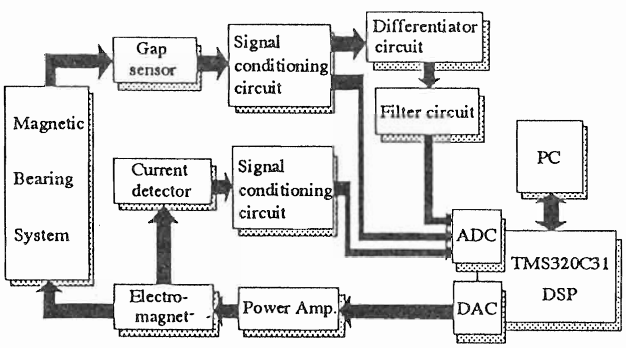


Fig.11 Controller block diagram representation

4.2 Solution to Control Problem

Using equations (6) and (7) for the stability of the system which is unstable in nature an optimum integral type servo control system has been constructed. Using this control system the experiment on the model has been carried out. Using MATLAB the non-linear Riccati equations is solved to obtain the feedback coefficients to stabilize the unstable system. An interactive program has been developed with the DSP which takes four gain parameters from keyboard and sends to the target program and the DAC output is represented as

$$e' = -\left(k_1 x' + k_2 \frac{dx'}{dt} + k_3 i' + k_4 \int x' dt\right) \qquad (8)$$

The parameters used for the solutions are listed in table 4.

Table 4 Parameters used in simulation

Parameter	Symbol	Value	Unit
Resistance	r	10.72	Ω
Inductance	L	1.936×10^{-1}	H
Constant	R	2380	—
	S	10800	—
Steady repulsive force	Flz	39.2	N
	Frz	39.2	N

5 Experimental Results

Using the above controller the experiments has been conducted and the rotor of the motor has been stabilized. The vibration of the rotor along x-axis is shown in fig.12 at steady state which is within 20 μ m. When disturbance is created the system shows overshoot and comes back to original condition fast represents the controller is robust in nature. Figs. 13(a) and (b) shows the vibration characteristics at turn-on and turn-off disturbance respectively. In this case a disturbance step function 0.5 mm has been created not by physically applying force on the rotor but by changing the reference input for the gap sensor. The system takes approximately 1 sec. to drive away out all the transients and returns to steady state. As the disturbance is created along x-axis, the rotor does not shift along z-axis and y-axis which has been confirmed by experiment.

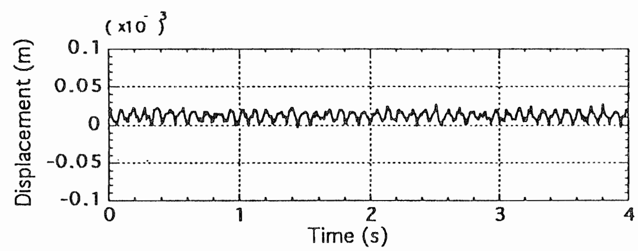
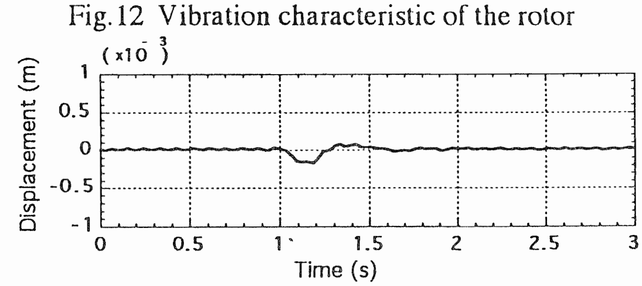
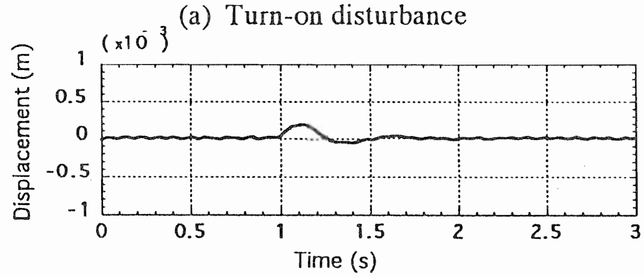


Fig.12 Vibration characteristic of the rotor



(a) Turn-on disturbance



(b) Turn-off disturbance

Fig.13 Vibration characteristic at disturbance

6 Conclusion

This paper has investigated a new type of permanent magnet configuration of repulsive type magnetic bearing system which has more stiffness characteristic resulting better stability of the overall system. By constructing an integral type servo control system and configuring the controller around the digital signal processor the rotor shaft has been stabilized in the desired position. The experimental results are also very much satisfactory.

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