Disturbance Attenuation and Faster Stabilization through Permanent Magnet Placement on Repulsive Type Magnetic Bearing

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journal or publication title	Proceedings of the International Conference on Power Electronics and Drive Systems
volume	1
page range	255-261
year	1997-05
URL	http://doi.org/10.24517/00048887

Proc. of the IEEE PEDS Conf., 255-261, May 1997.

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Abstract - Repulsive type magnetic bearing consisting of permanent magnets(PM) and controlled current electromagnets have the advantages of less number of electromagnets and simplified control circuit compared to active magnetic bearing. The system is fundamentally unstable one and is very prone to disturbance. The shape and configuration of permanent magnet has a strong influence on the stability of the system. Two model of repulsive type magnetic bearing have been designed and fabricated in our laboratory. Repulsive forces and stiffness characteristics for different PM configurations have been studied and suitable configuration have been chosen. This paper investigates a method of disturbance attenuation and faster stabilization via permanent magnet configuration on repulsive type magnetic bearing.

1. Introduction

Repulsive Type Magnetic Bearing using permanent magnets for the levitation and radial control makes the system cheap and simplified control scheme[1]-[4]. But the system is prone to disturbance in absence of any active control. Active Magnetic Bearings(AMB) because of their adjustable damping and stiffness characteristics in all directions are widely accepted in the industrial applications. The controllers for AMBs are very complicated in nature and incur high cost. If some low cost solution is provided then repulsive type magnetic bearing will be attractive in commercial applications. The magnetic bearing system described here is basically a single axis control system resulting a simplified controller. The better performance along the uncontrolled radial direction have been achieved by their proper placement of the permanent magnets in bearing system.

The electrical machines employing repulsive type magnetic bearings may be of two types. (1) Vertical shaft machines and (ii) Horizontal shaft machines. In both types of machines the repulsive force acting between stator and rotor permanent magnet is mainly used to levitate the rotor of the motor. In type (i) the direction of levitation and radial stiffness are decoupled resulting better control on radial stiffness and higher stiffness can be achieved as shown in [5]. As they are coupled to each other in type (ii), there must be some trade-off between the two. As higher stiffness is desirable from the disturbance attenuation viewpoint, placement of permanent is utmost important. This paper investigates the permanent magnet configuration achieving improved radial stiffness resulting better disturbance attenuation characteristics. This system can be used in fly-wheel energy storage and other such applications in presence of small radial disturbance.

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 magnet having 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. The configuration of permanent magnet in the bearing system is shown in Fig.2. Both the permanent magnets are made of Sr-Ferrite magnet.

2.2 Repulsive forces, Stiffness and PM Configuration

The radial stiffness of the system described above is low resulting poor radial disturbance attenuation characteristic. To improve the stiffness characteristics PM configuration have been investigated in this paper. Placing permanent magnet in the upper part of the stator as shown in Fig.3 improves the stiffness to some extent at the sacrifice of repulsive force. We have calculated repulsive

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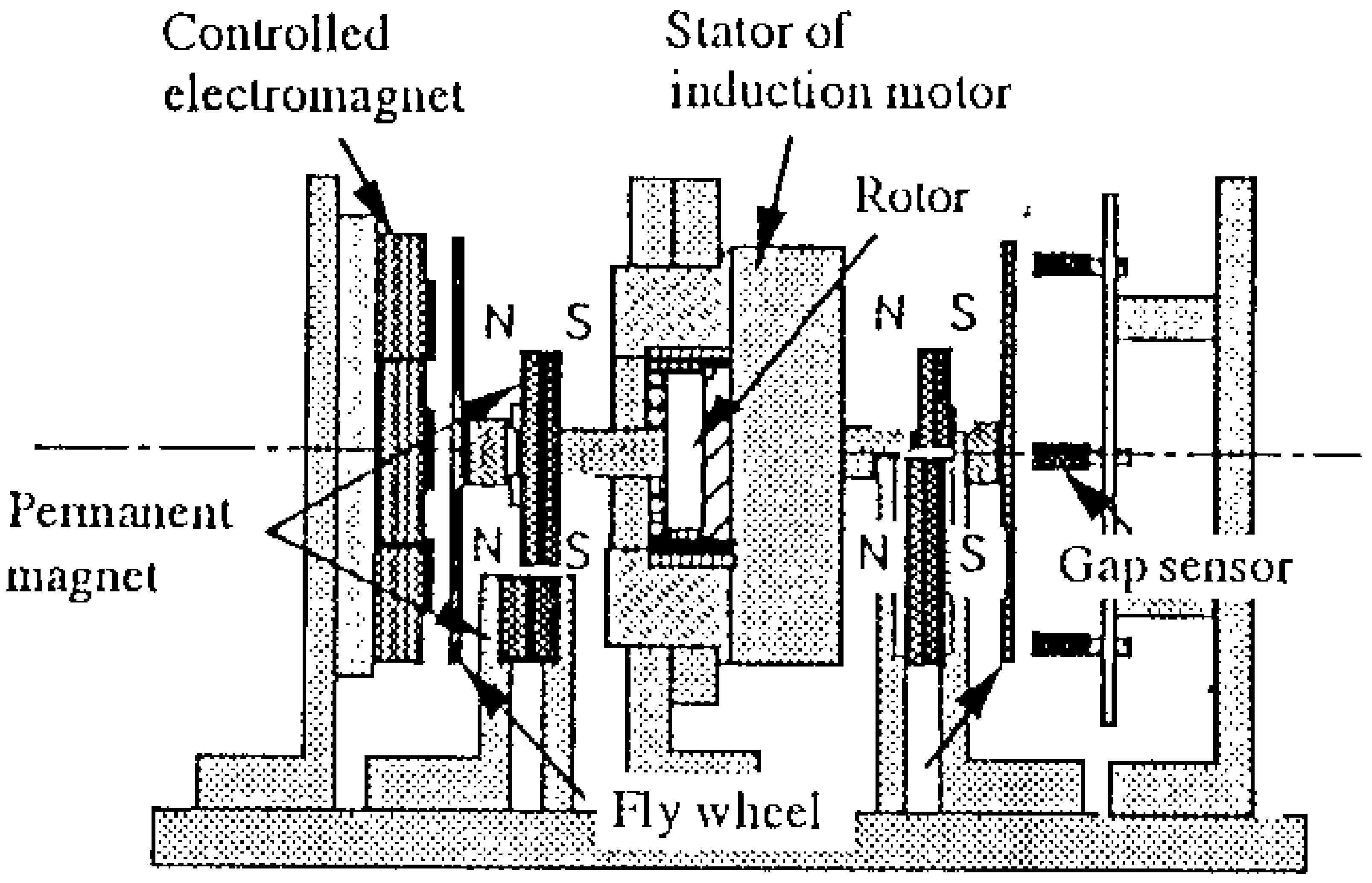


Fig. 1 : Magnetic Bearing System - Previous Model

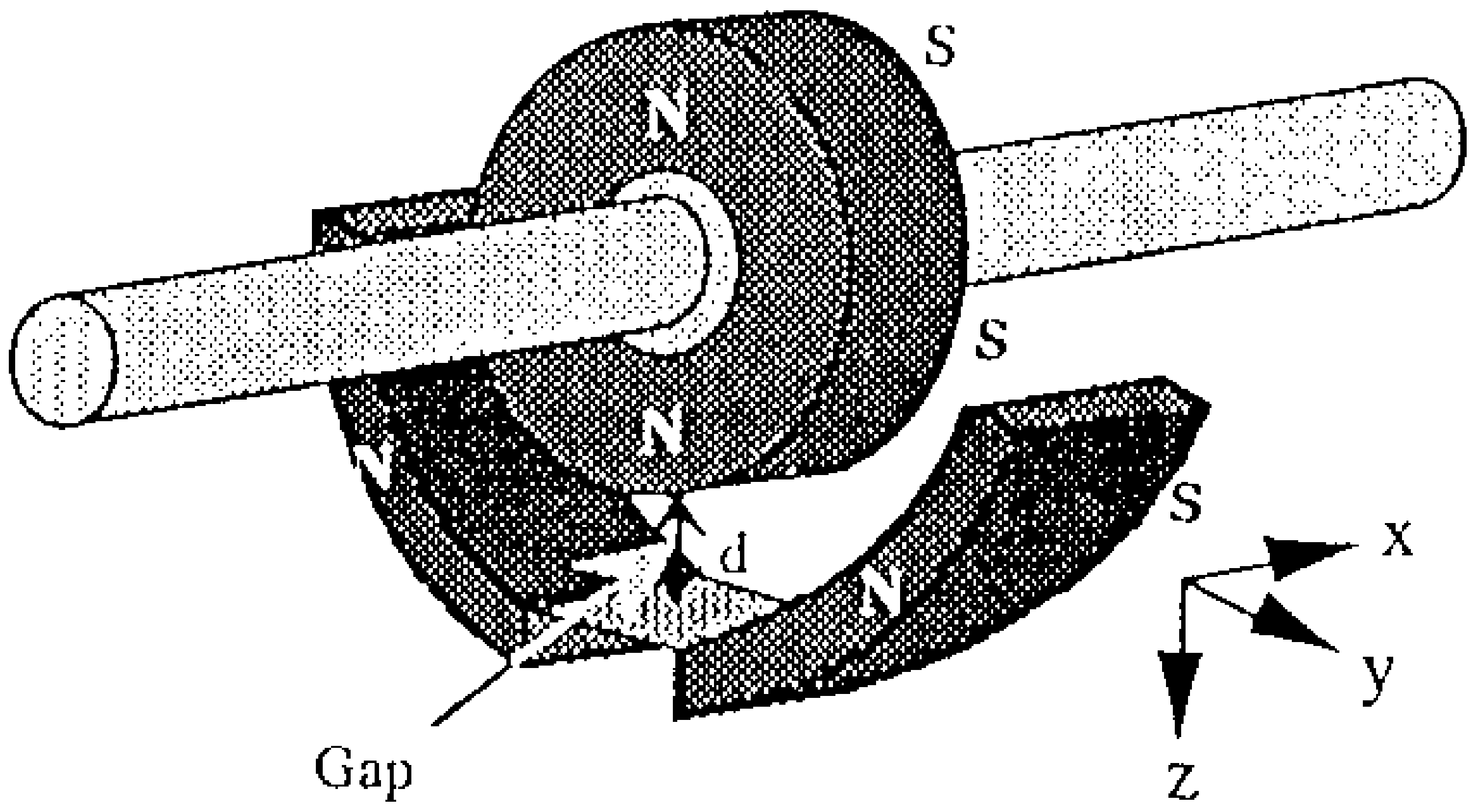


Fig.2 : Permanent Magnet Configuration

forces as well as stiffnesses with different permanent magnet sections at the upper stator part using finite element method. Fig.4 shows the variation of repulsive force with gap distance for different section of PMs such as θ = 0° (No upper stator magnet), 30°, 45°, 60° and 90° etc. Fig.5 shows the variation of stiffness characteristics of the above. It is seen from Figs. 5 and 4, that the stiffness characteristics has been improved with the reduction of repulsive forces. As repulsive force is very much important to levitate the rotor, there must be a trade-off between the two. The magnitude of the forces and stiffnesses obtained from finite element method is higher than that obtained experimentally.

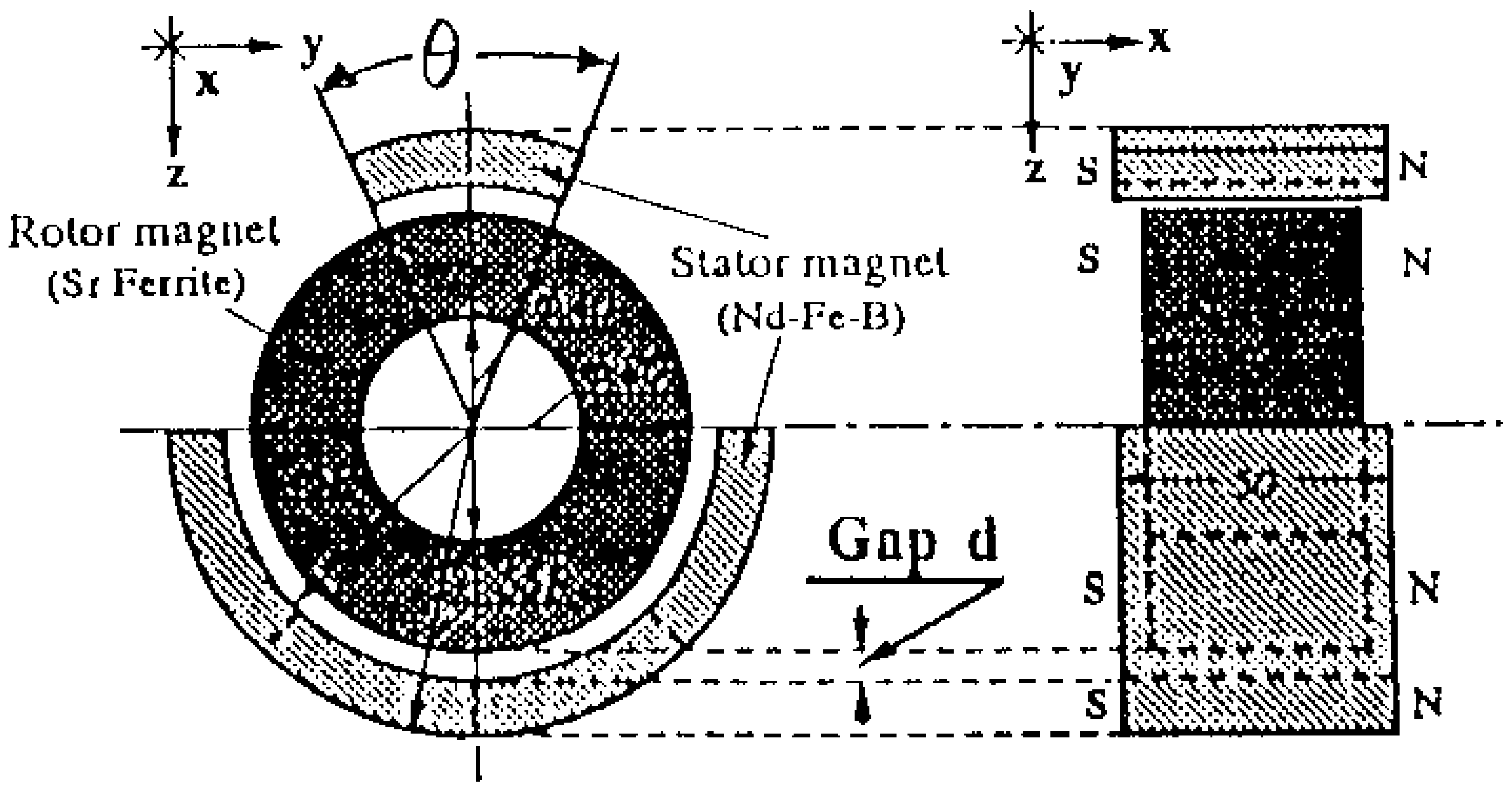


Fig.3 : Placement of Upper Stator Magnet

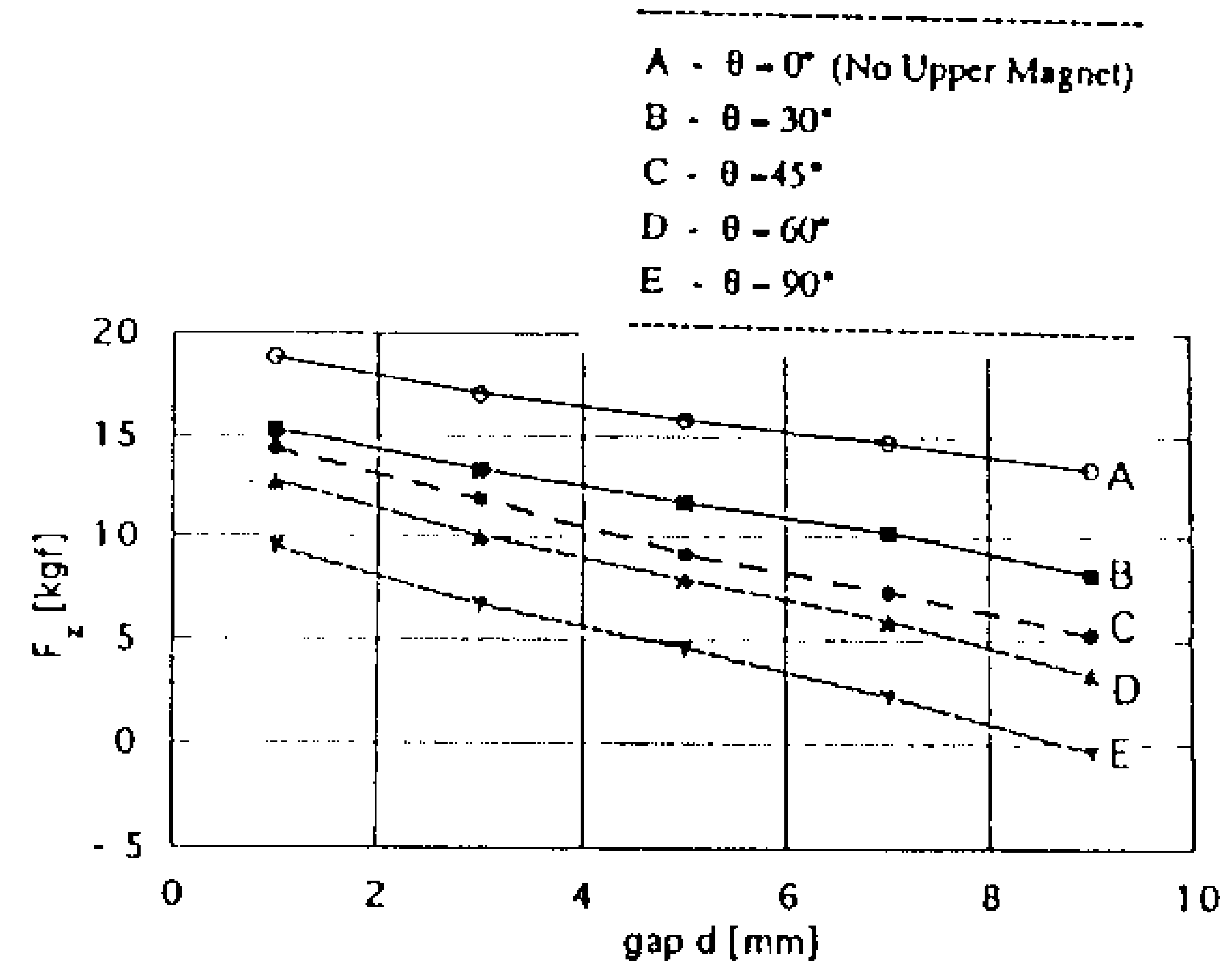


Fig.4 : Repulsive Force Characteristics for Different Upper Stator Magnet Sections

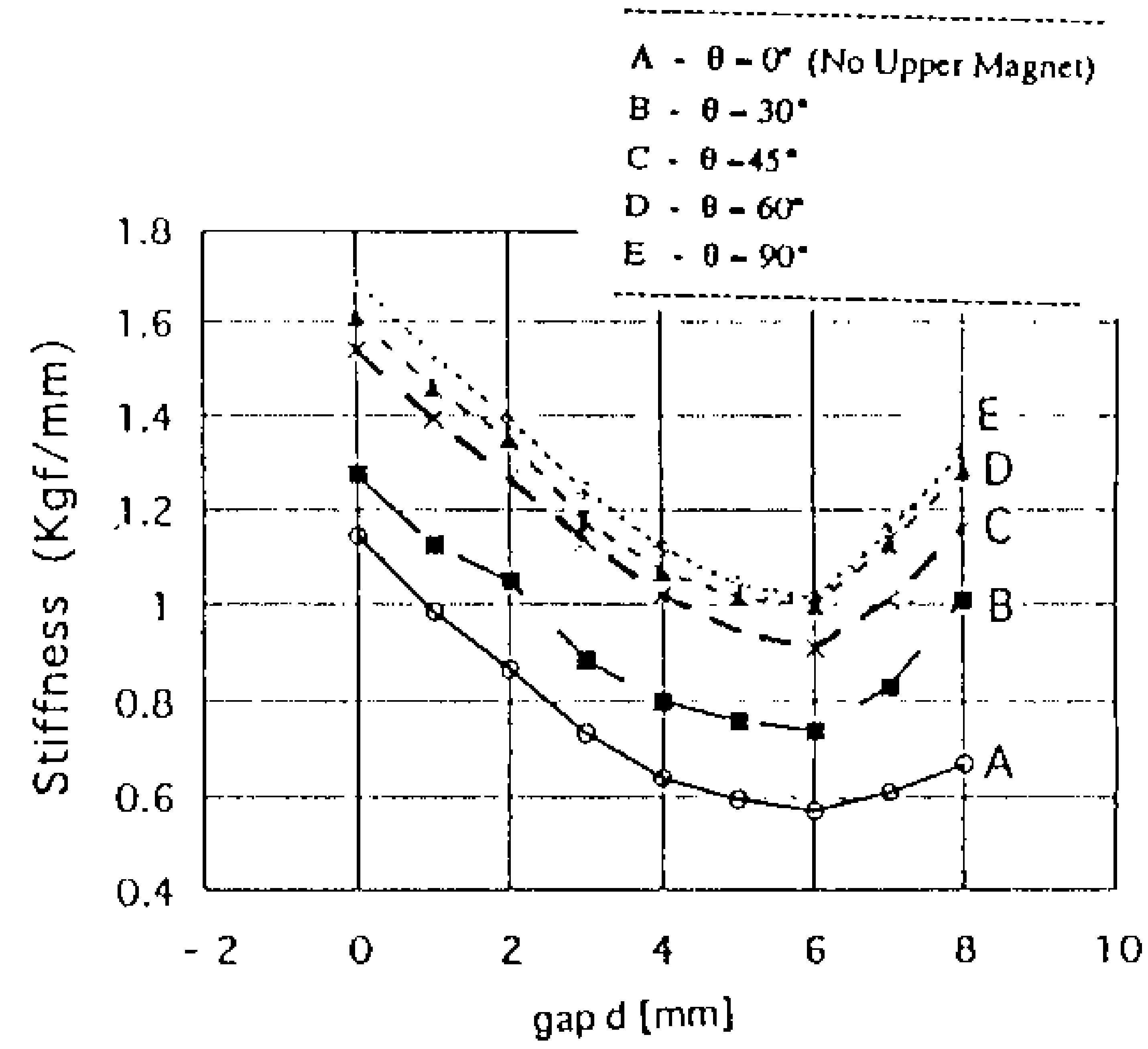


Fig.5 : Calculated Stiffness Characteristics of Fig.4

2.3 Configuration of Present System

Based on the above discussion in order to levitate a rotor having mass of 8kg with a gap of 4mm between the stator and rotor, we have taken PM configuration corresponding to θ = 45° (experimental value of repulsive force) and the second model have been developed in the laboratory. The configuration of the present system is shown in Fig.6 and the corresponding magnet configuration is shown in Fig.7. The stator is made up of NdFeB permanent magnet and the rotor is of Strontium Ferrite magnet. The rotor itself acts as a fly-wheel in this system. The total mass of the rotor is 8kg.

3. Characteristics of Repulsive Forces

The magnitude of the repulsive forces acting in three direction have been calculated with the help of finite element method as well as measured experimentally.

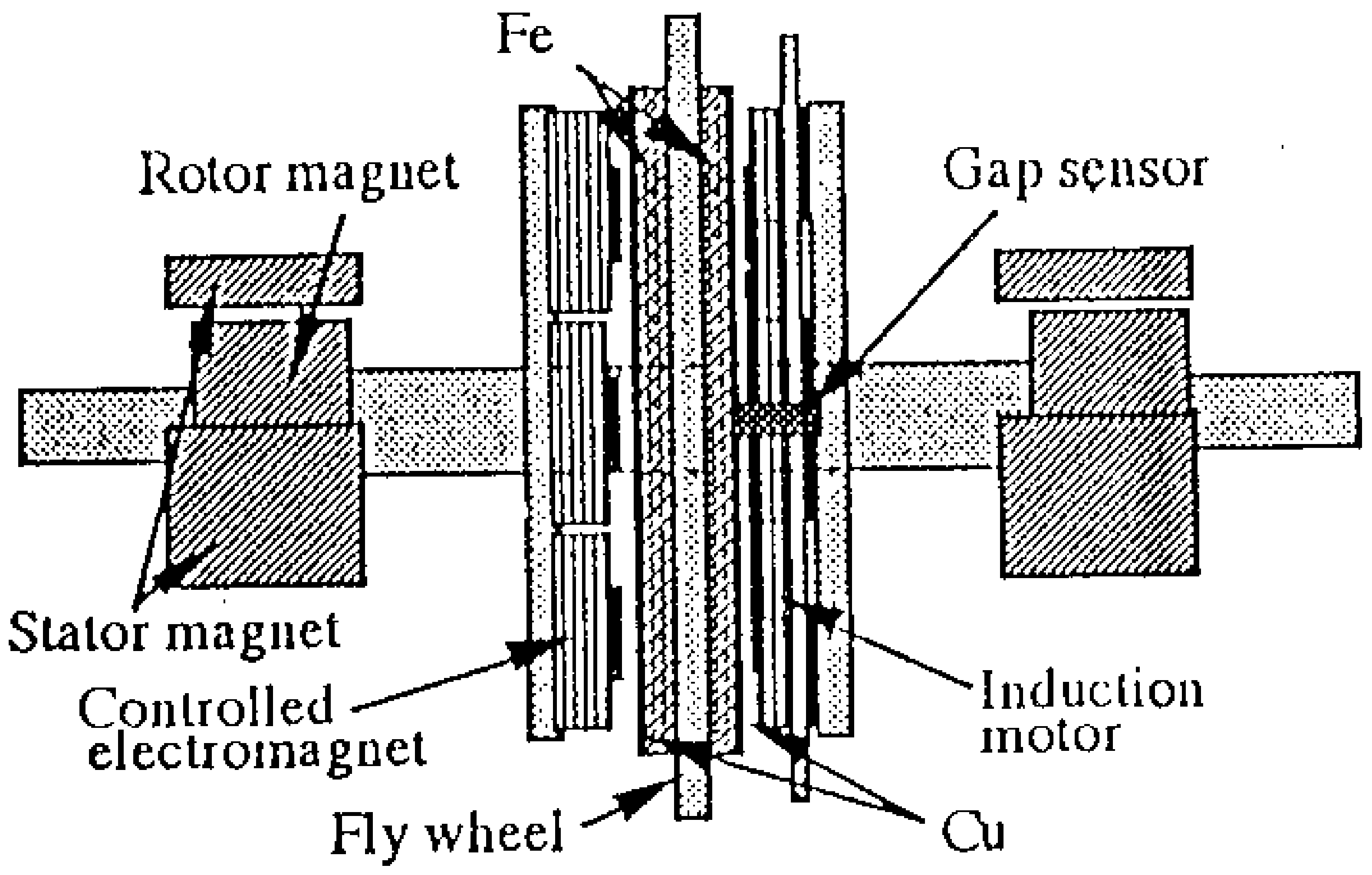


Fig.6 : Magnetic Bearing System - Present Model

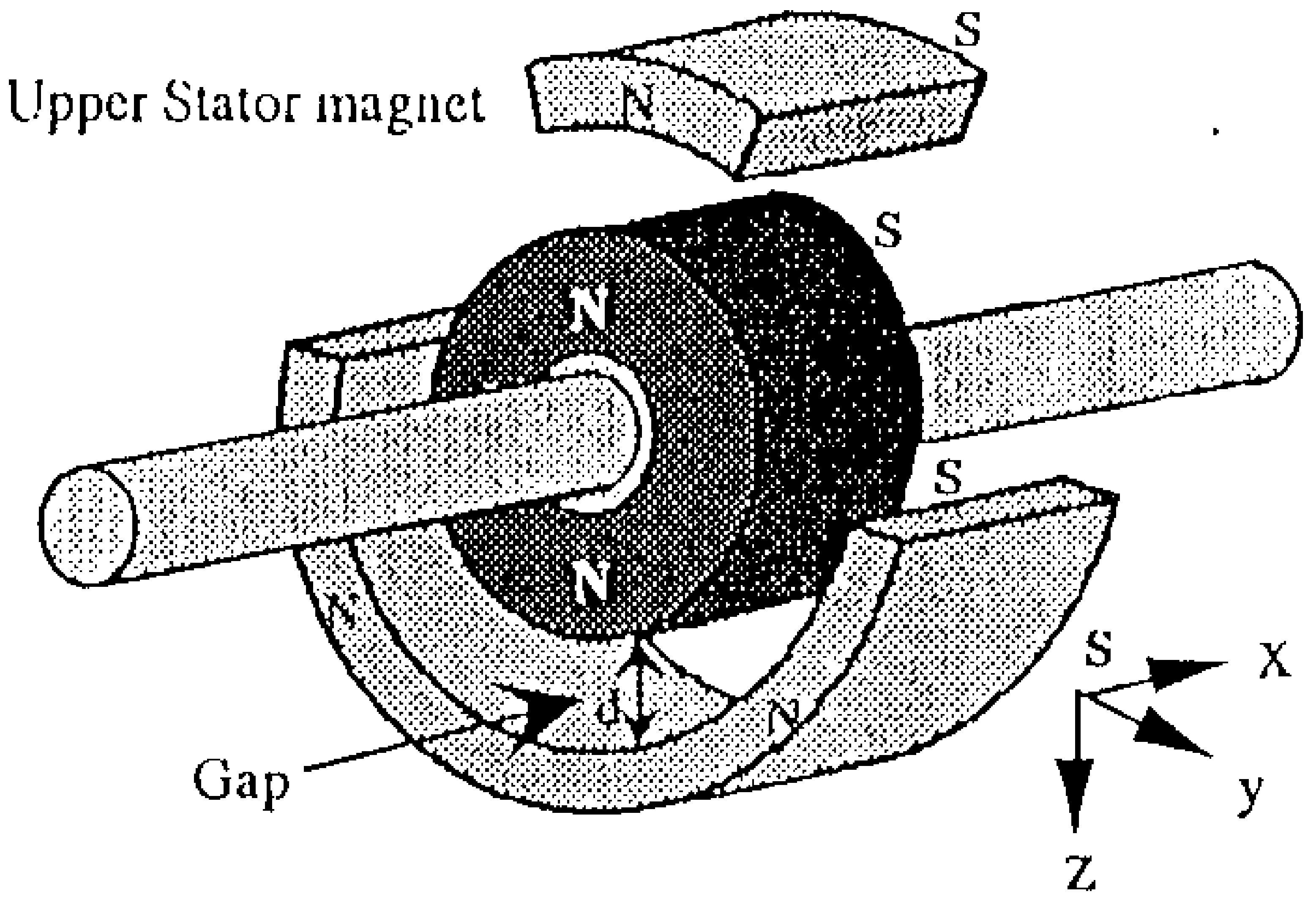


Fig.7 : Permanent Magnet Configuration

The experimental values are of more significant here. The nature of repulsive forces in three direction of the present system have been discussed and compared with that of other system i.e., without upper stator magnet.

The variation of repulsive force along z-axis, f_z with the gap for different values of x are shown in Fig.8 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.9 and 10 respectively. The variation of stiffnesses along z-axis with and without upper stator magnet is shown in Fig. 11.

Considering the operating point x=1mm and d=4mm, the stiffness along z-axis with upper stator magnet is around 2.4 times to that of without one which helps to improve stability of the system.

4. System Modeling

The forces acting on the rotor are shown in Figs.12a and 12b for the two models respectively. The details of the modeling have been discussed in [7]-[9]. The forces experienced by the permanent magnets in the x, y and z directions as shown in Figs. 8, 9 and 10 are expressed by approximate equations as shown below.

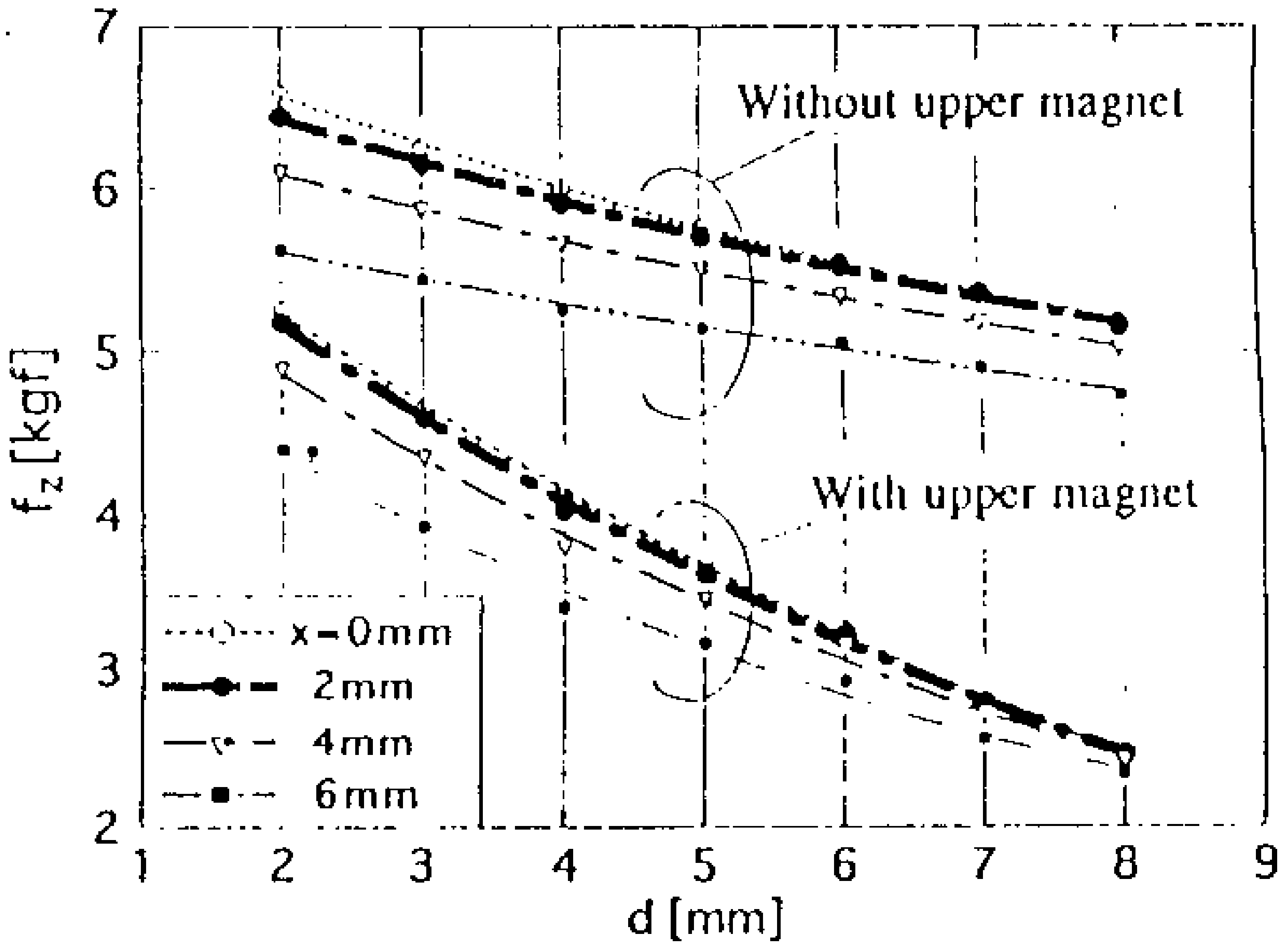


Fig.8 : Repulsive Force Characteristic along z-axis

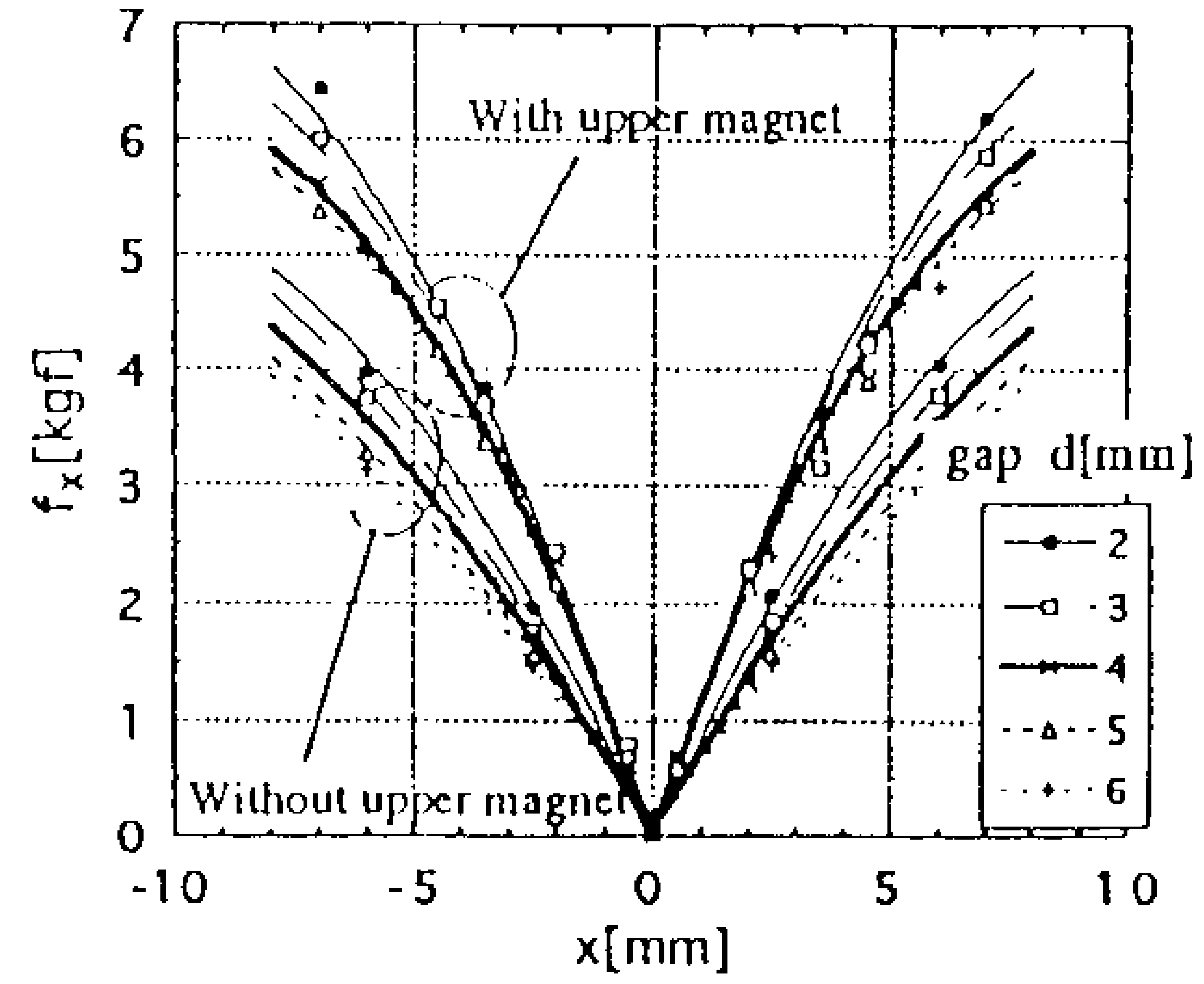


Fig.9 : Repulsive Force Characteristic along x-axis

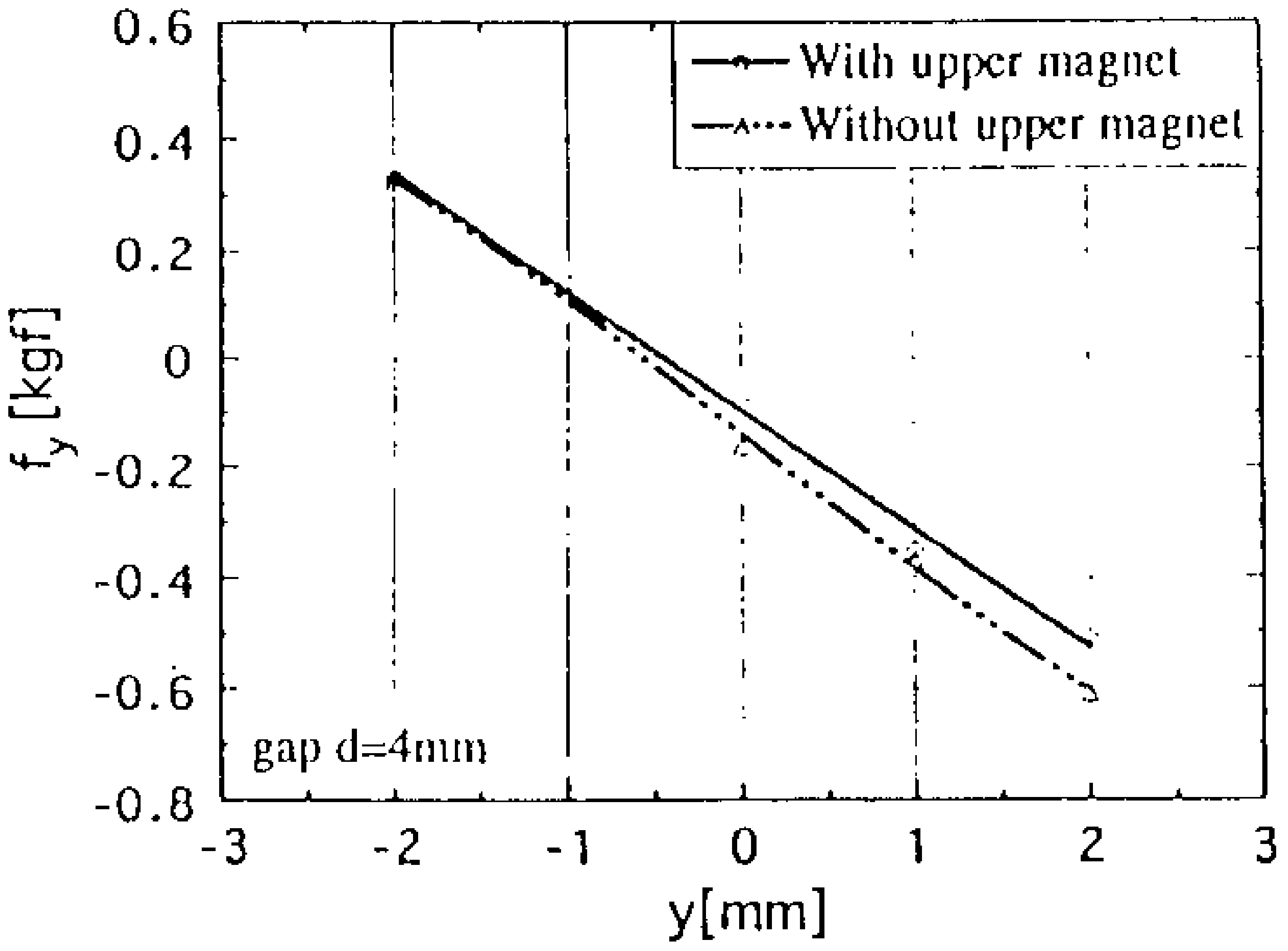


Fig.10 : Repulsive Force Characteristic along y-axis

Along x-axis :

$$f_c = Sg_c - 2F \quad (c = l_x, r_x) \qquad (1)$$

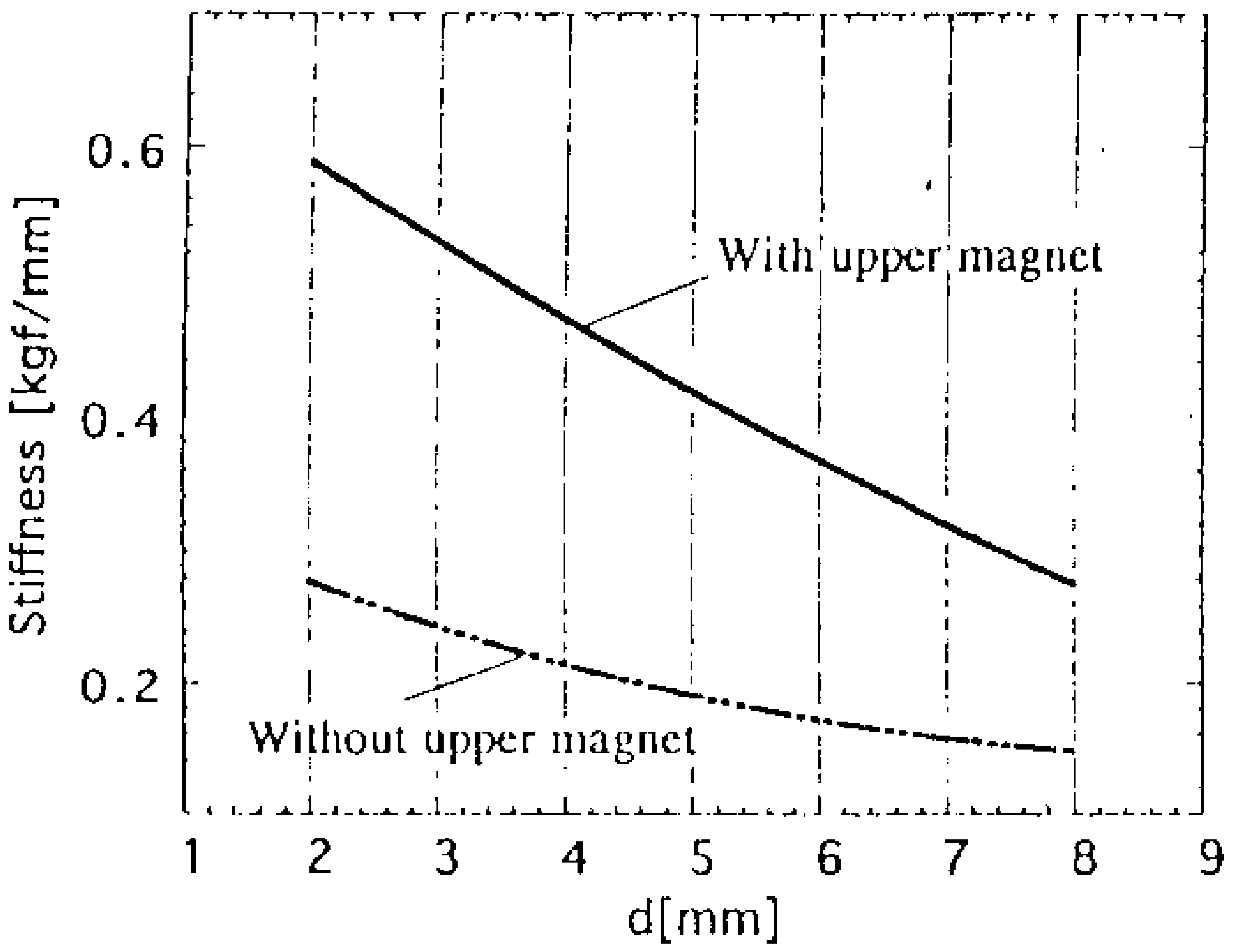
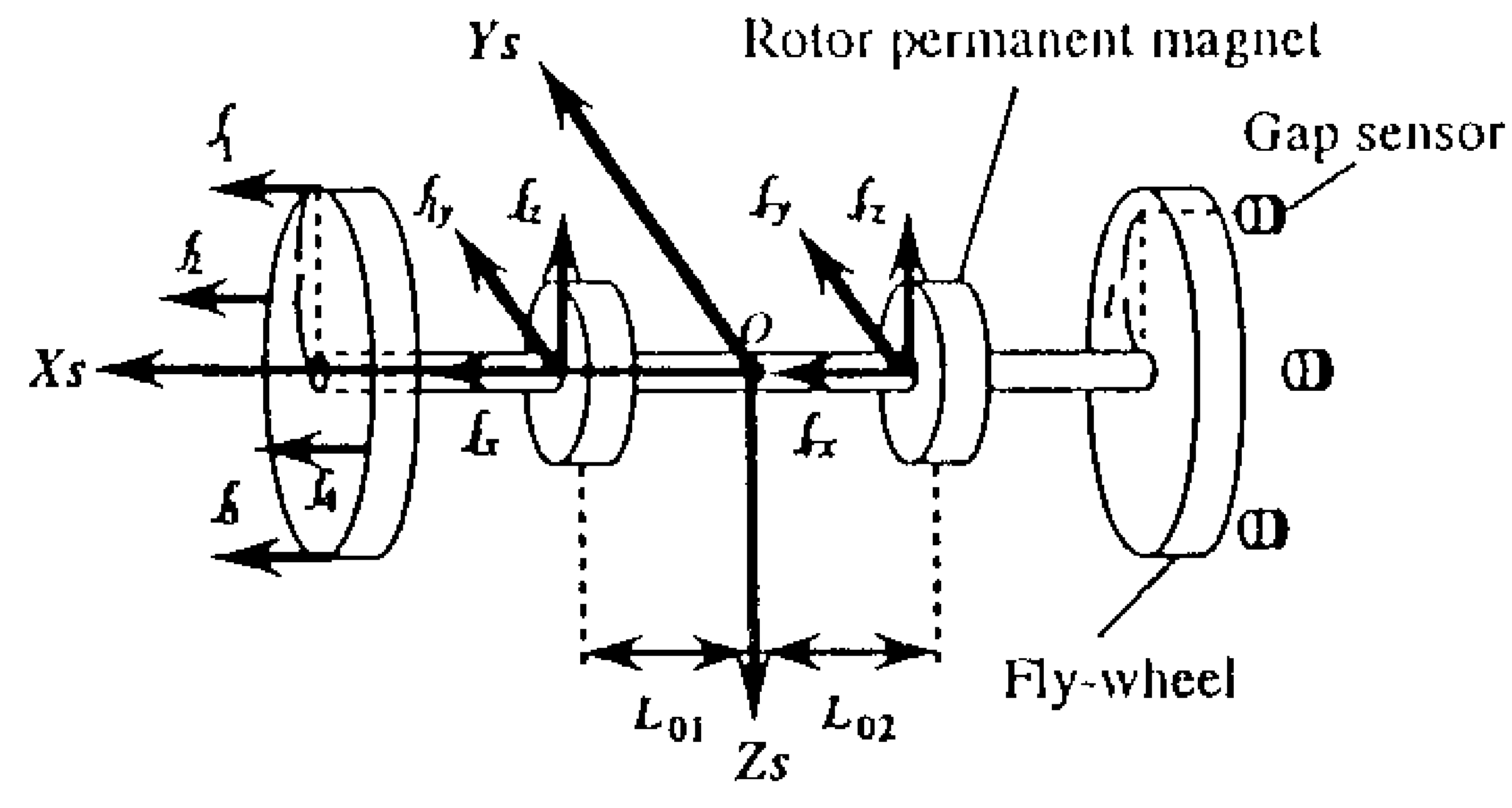
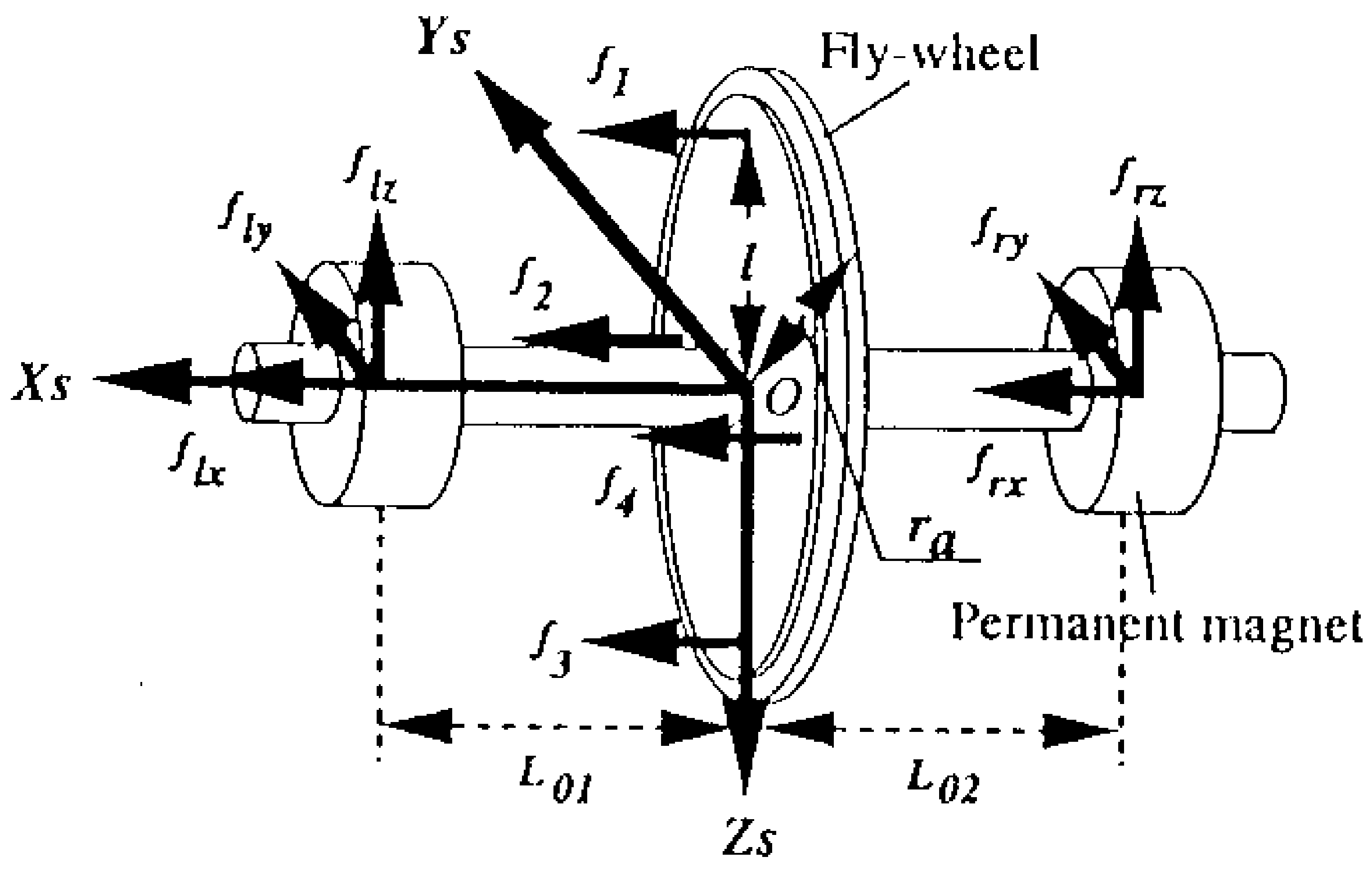


Fig.11 : Stiffness Characteristic along z-axis



a) Previous model



b) Present model

Fig.12 : Modeling of Rotor

Along y-axis :

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

Along z-axis :

$$fa = Q/g_a \qquad (a = l_z, r_z) \qquad (3)$$

where S, F, R and Q have got different values with and without upper stator magnet. Changing the reference point and linearizing around the nominal operating point, the equations can be written as

$$\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \begin{bmatrix} \partial f_x/\partial x & \partial f_x/\partial y & \partial f_x/\partial z \\ \partial f_y/\partial x & \partial f_y/\partial y & \partial f_y/\partial z \\ \partial f_z/\partial x & \partial f_z/\partial y & \partial f_z/\partial z \end{bmatrix}_{at\, x_0, y_0, z_0} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (4)$$

The partial derivatives are calculated from the experimental characteristics at the nominal operating point. Taking the deviations along the linear displacements in three directions, the pitch and yaw and their derivatives and the deviations of current from the nominal operating point as the state variables, the state space equations are represented as

State-space equation

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix} = \begin{bmatrix} 0 & I & 0 \\ B_1D_1 + B_2C_2 & A_1 & B_2C_3 \\ 0 & 0 & -L^1RI \end{bmatrix}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ L^1I \end{bmatrix} e \qquad (5)$$

Output equation

$$y = \begin{bmatrix} C_1 & 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ z \\ i \end{bmatrix}. \qquad (6)$$

where

$$x_1 = \begin{bmatrix} x, & y, & z, & \theta & \varphi \end{bmatrix}^T$$

$$z = \dot{x}_1$$

$$i = \begin{bmatrix} i_1' & i_2' & i_3' & i_4' \end{bmatrix}^T$$

$$e = \begin{bmatrix} e_1' & e_2' & e_3' & e_4' \end{bmatrix}^T$$

The values of A_1, B_1, B_2, C_1, C_2, C_3 and D_1 are given in [9].

5. Simulation

To simulate the effect of disturbances in the state space model as shown in [5] and [6], the block diagram representation of the simulation model is shown in Fig.13. Simulation characteristics are obtained using the MATLAB Simulink simulation software package. By applying disturbance at the input the responses are obtained. By setting the proper parameters in the model the simulations of the bearing systems with and without upper stator magnet are done. The parameter values for the feedback coefficients matrix K are obtained using MATLAB by solving Riccati equation for an Optimum Integral type servo control design. Fig.14a shows the disturbance characteristic along z-axis without upper stator magnet and Fig.14b shows the disturbance characteristics along z-axis with upper stator magnet. As there is passive radial bearing the vibration characteristics along the z-axis is of interest. It is seen that the effect for the same level of disturbance force is less for the model having upper stator magnet.

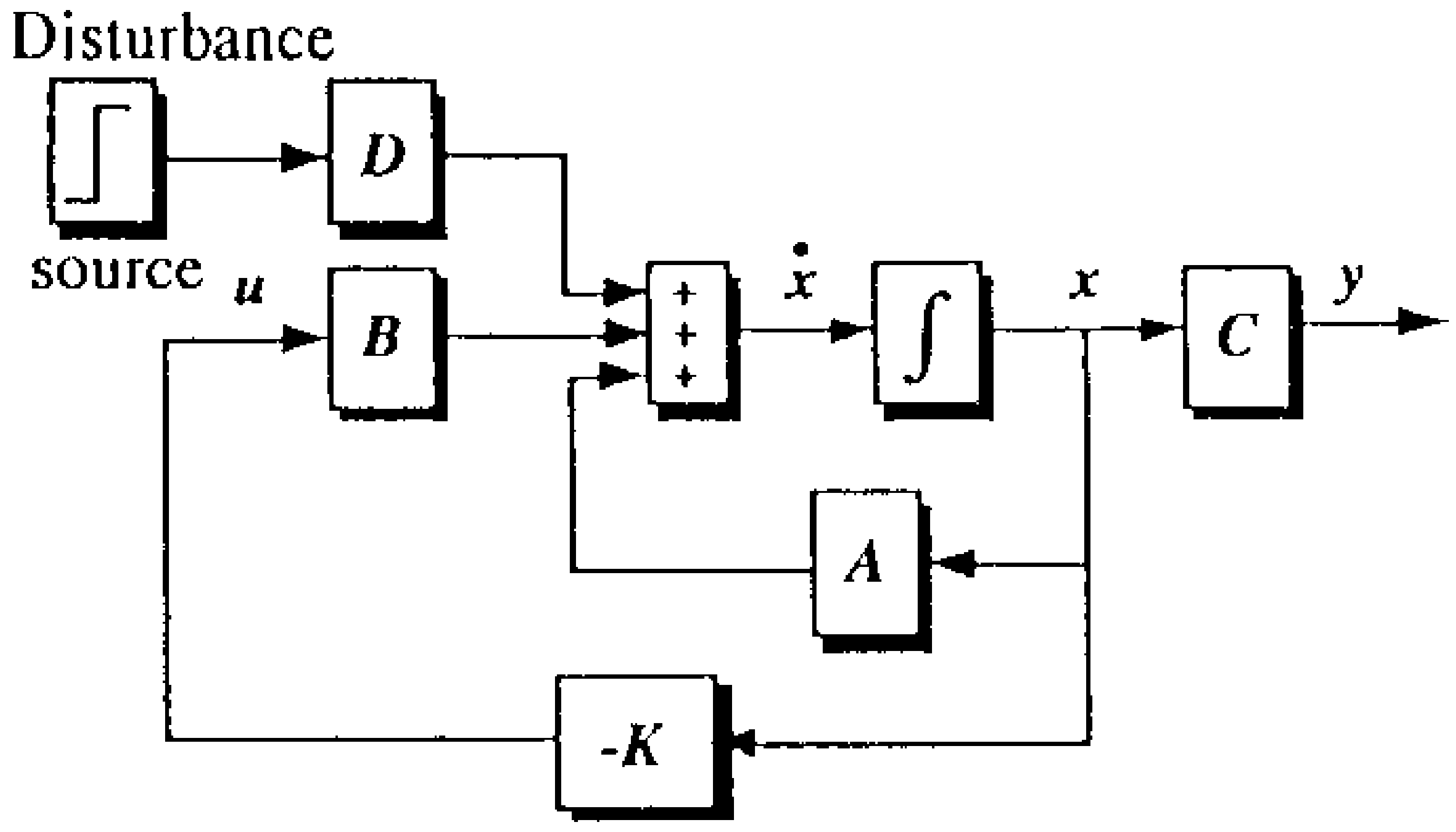
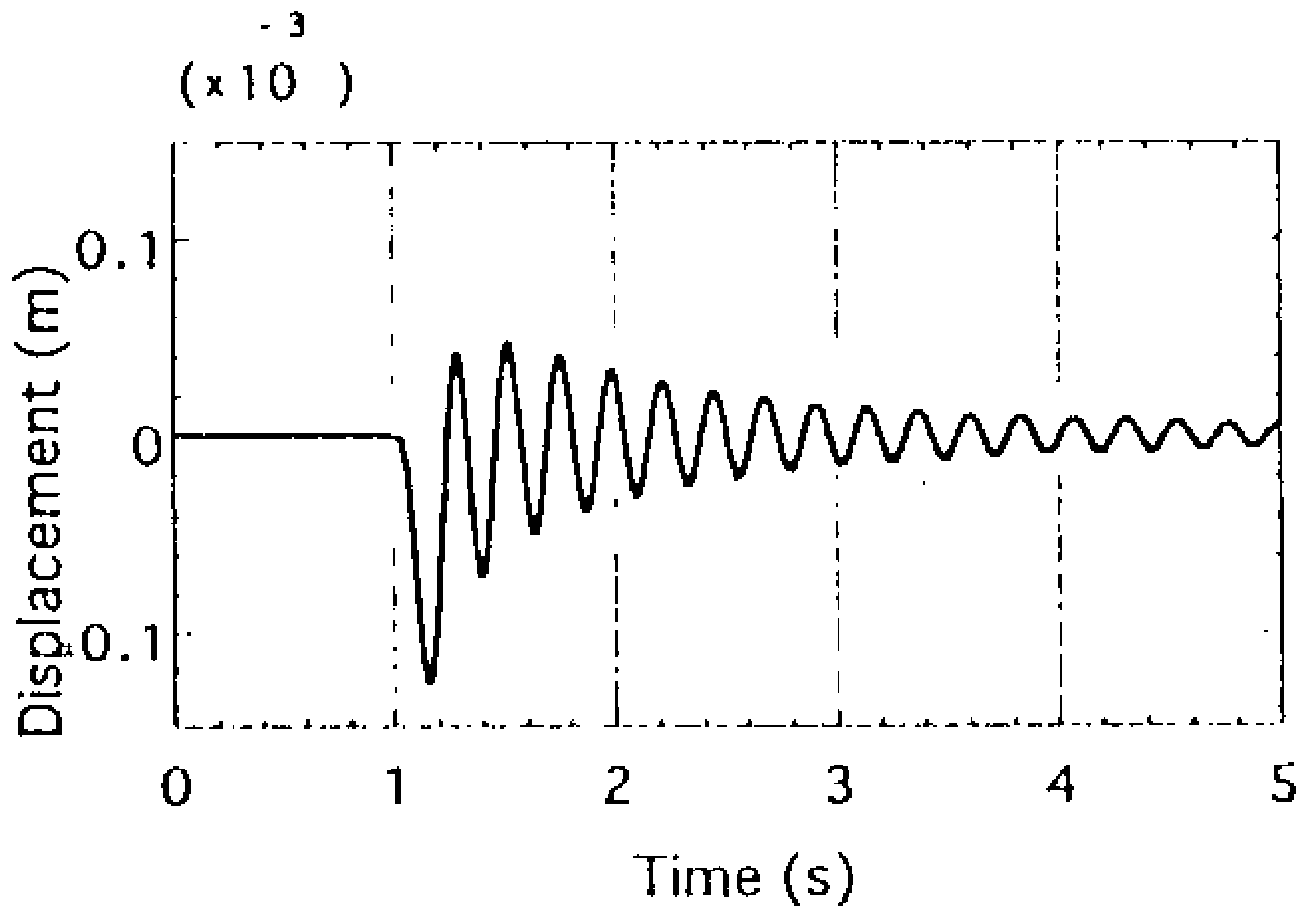
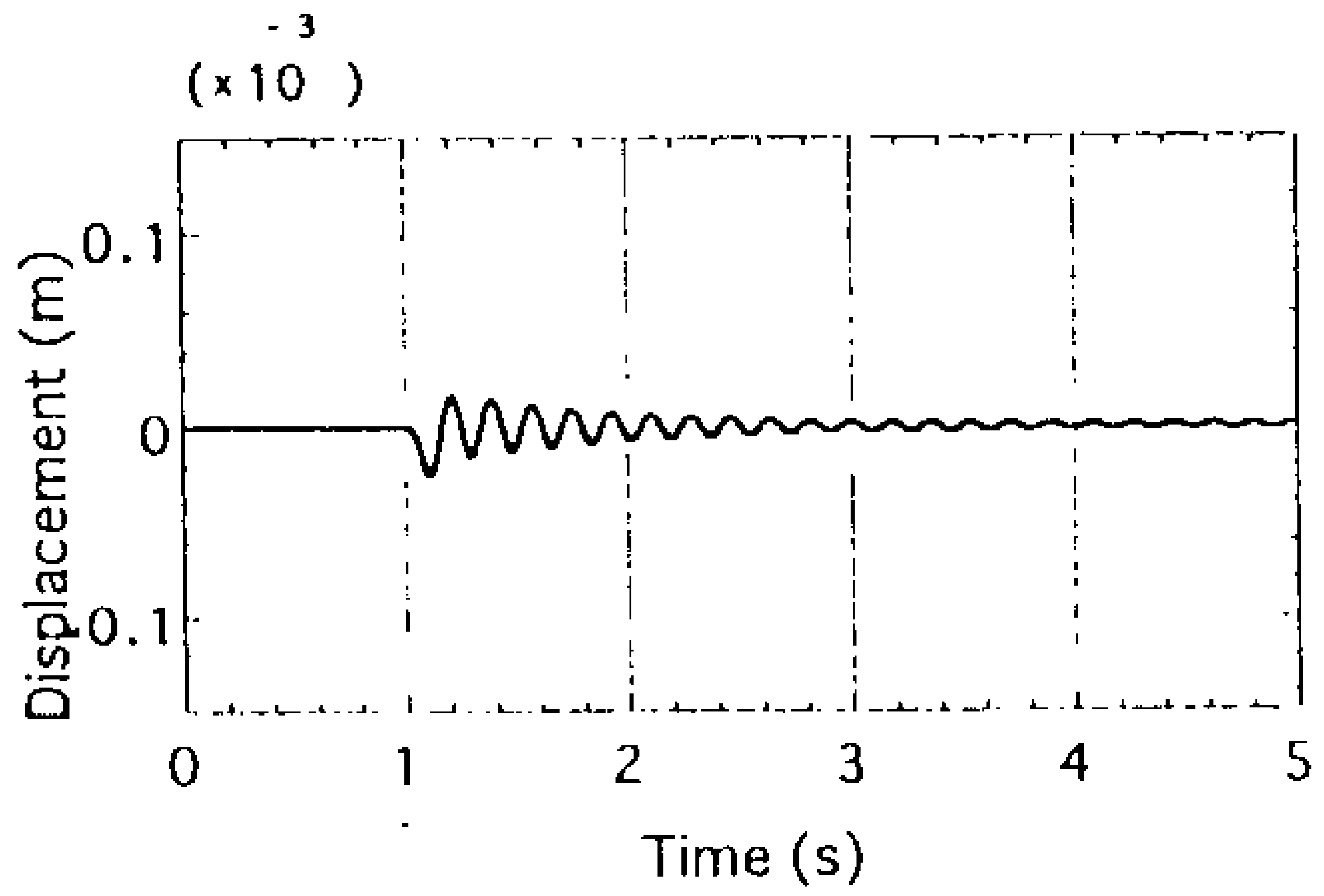


Fig.13 : Block diagram representation of Simulation Model



a) Without Upper Stator Magnet



b) With Upper Stator Magnet

Fig.14 : Simulated Disturbance Characteristics along z-axis

6. Experimentation

The controller has been configured around a digital signal processor kit. The block diagram representation of the control system is shown in Fig.15. The inputs to the controller are the gap-displacement, its derivative and the current. For the control purposes a simplified scheme has been used with only one gap-sensor and all the electromagnets are connected in series. Using the above controller the experiments have been conducted and the rotor of the motor have been stabilized. The vibration of the rotor along x-axis is shown in Figs.16a and 16b at steady state with and without upper stator magnet. It is seen that the steady state vibration level of the rotor is 10 micrometer for both the models. This is possible by proper selection of gain parameters of the controller due to the presence of active controller along the x-axis. When disturbance is created the system shows overshoot and comes back to original condition after sometime. The disturbance is a step function of 0.5mm which corresponds to a force of 0.65 kgf, has been created not by physically applying force on the rotor but by adding it to the feedback signal of the gap-sensor. Figs.17a and 17b shows the vibration characteristics at turn-on disturbance along x-axis and z-axis respectively with upper stator magnet. The corresponding characteristics for the model without upper stator magnet are shown in Figs.18a and 18b respectively. It is seen that the maximum overshoot along x-axis with both the model is nearly equal and around 0.2mm. But along the z-axis the maximum overshoot is 0.2mm with upper stator magnet but with the other model without upper stator magnet it is nearly 0.6mm i.e., almost 3 times. Difference of time taken for stabilization is also appreciable. With upper stator magnet the system takes around 0.7sec to settle down but it is approximately 3 sec for the other model. This is due to the improved stiffness characteristic along z-axis in presence of upper stator magnet[10].

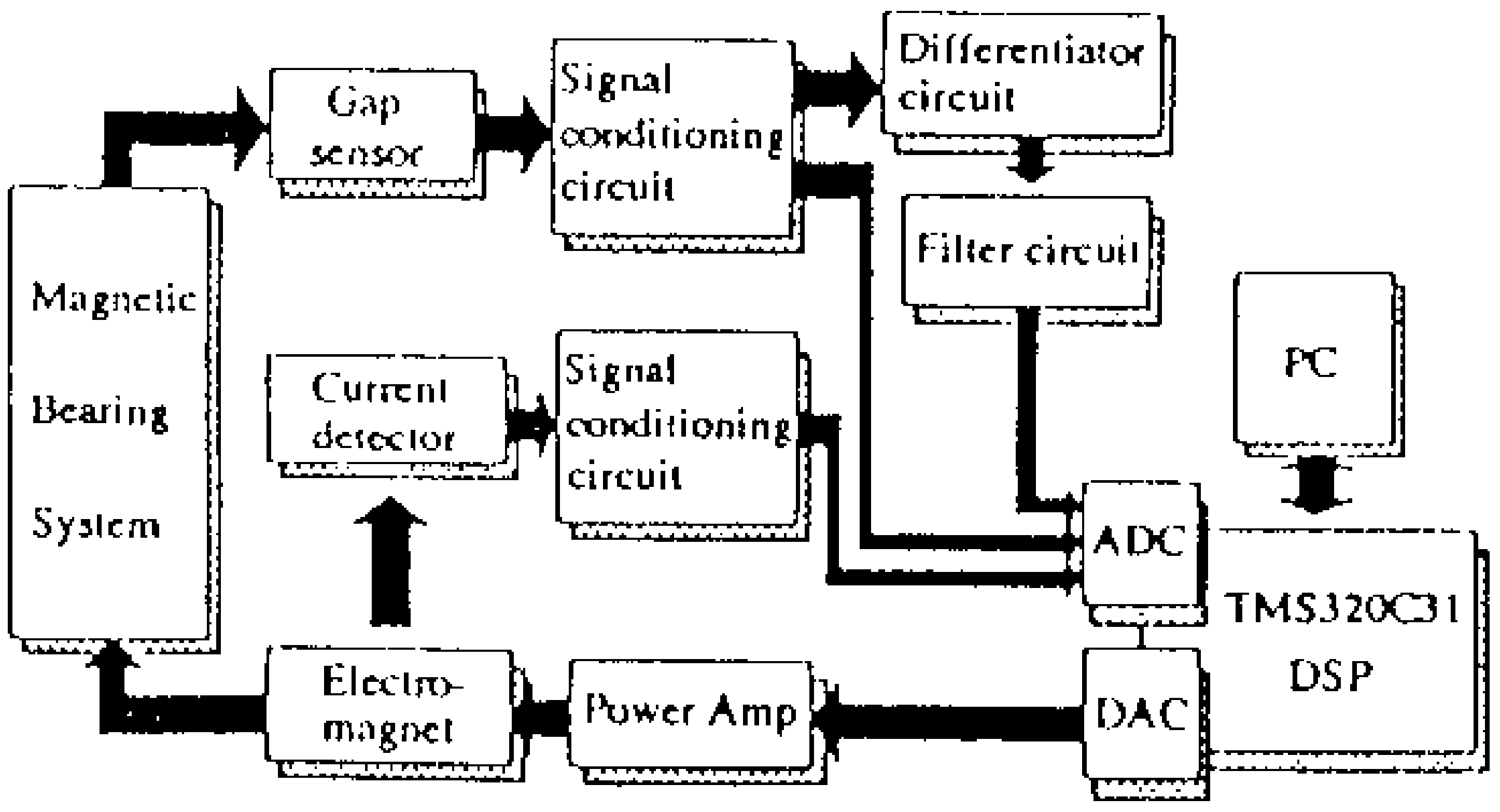
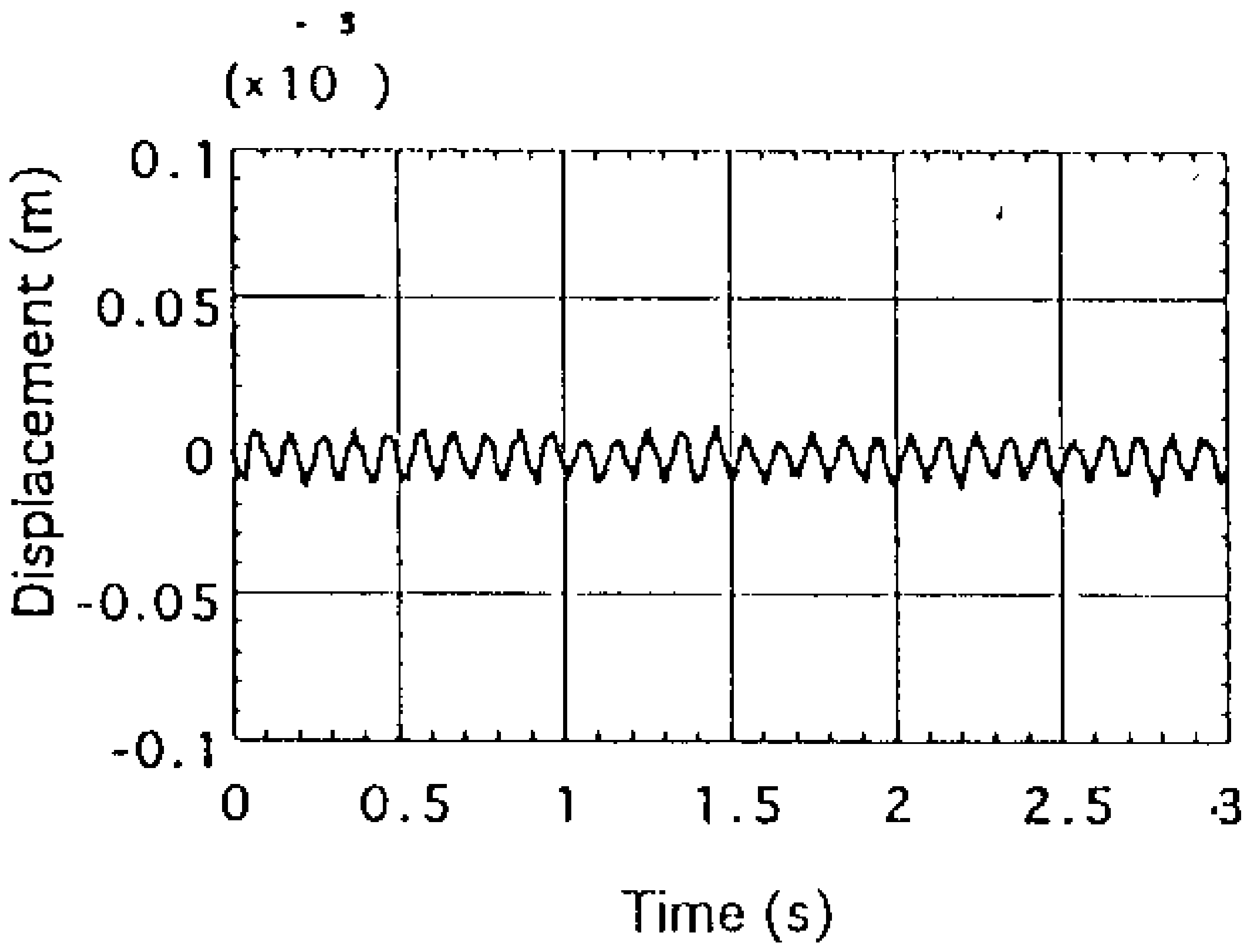
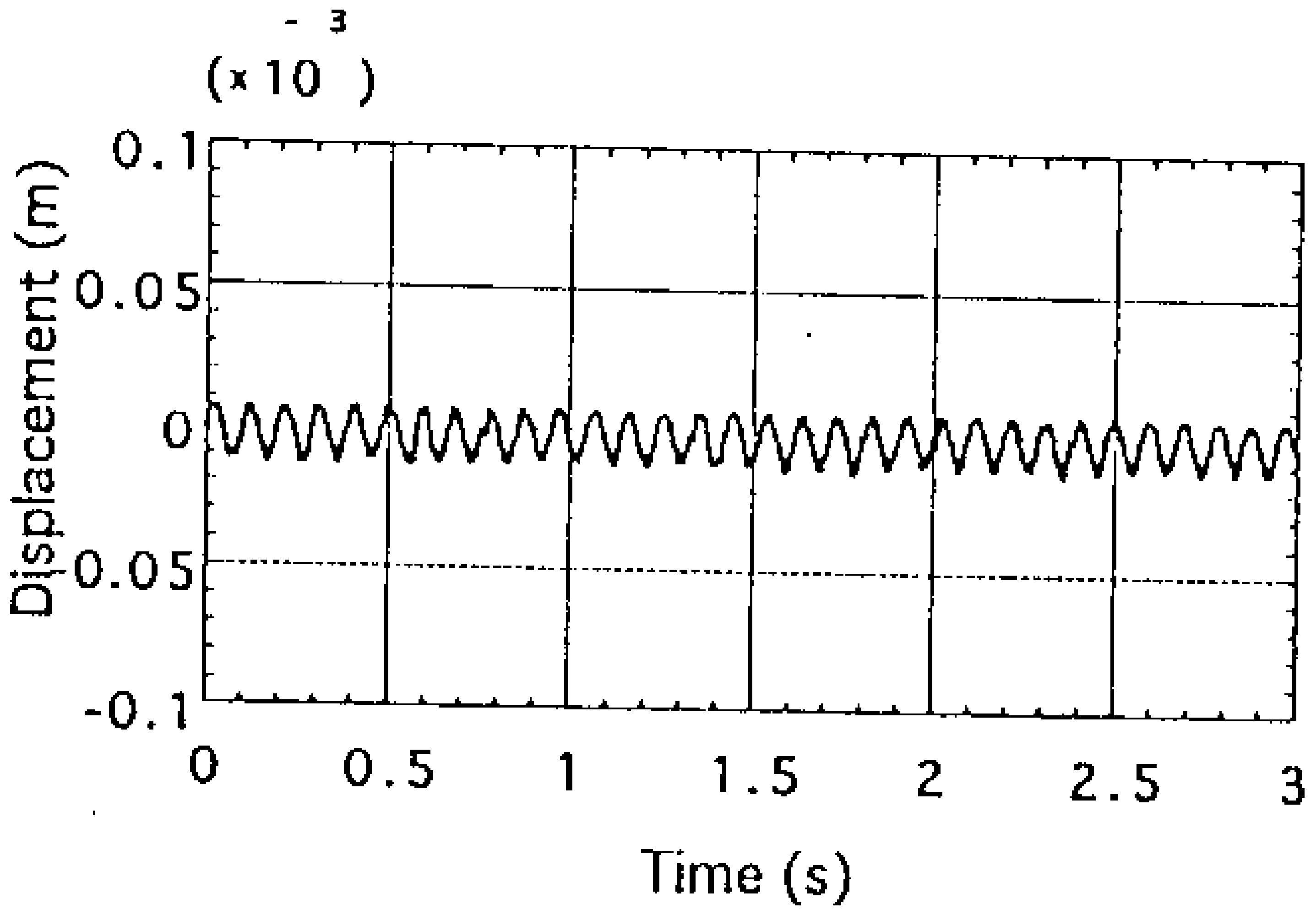


Fig.15 : Controller Block Diagram Representation

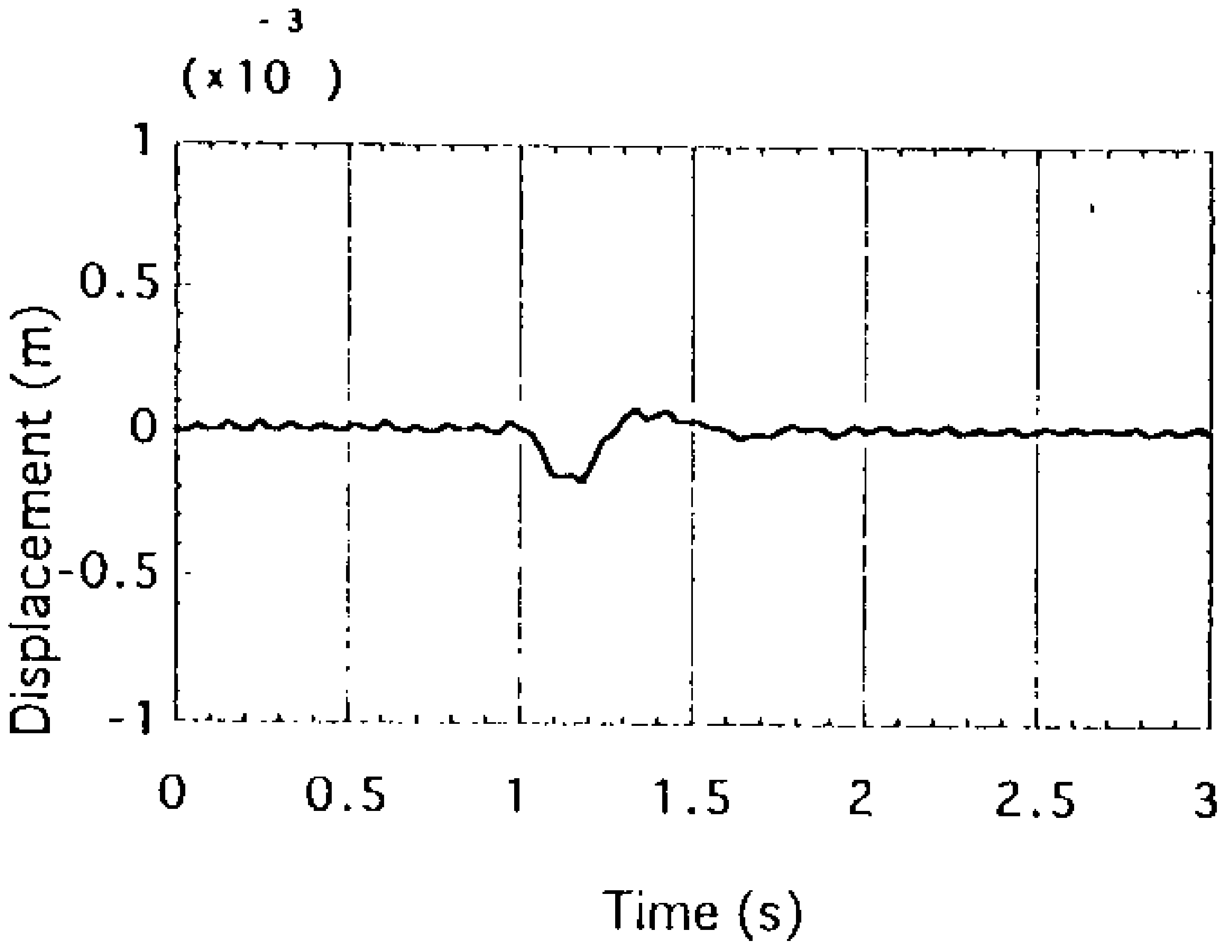


a) With Upper Stator Magnet

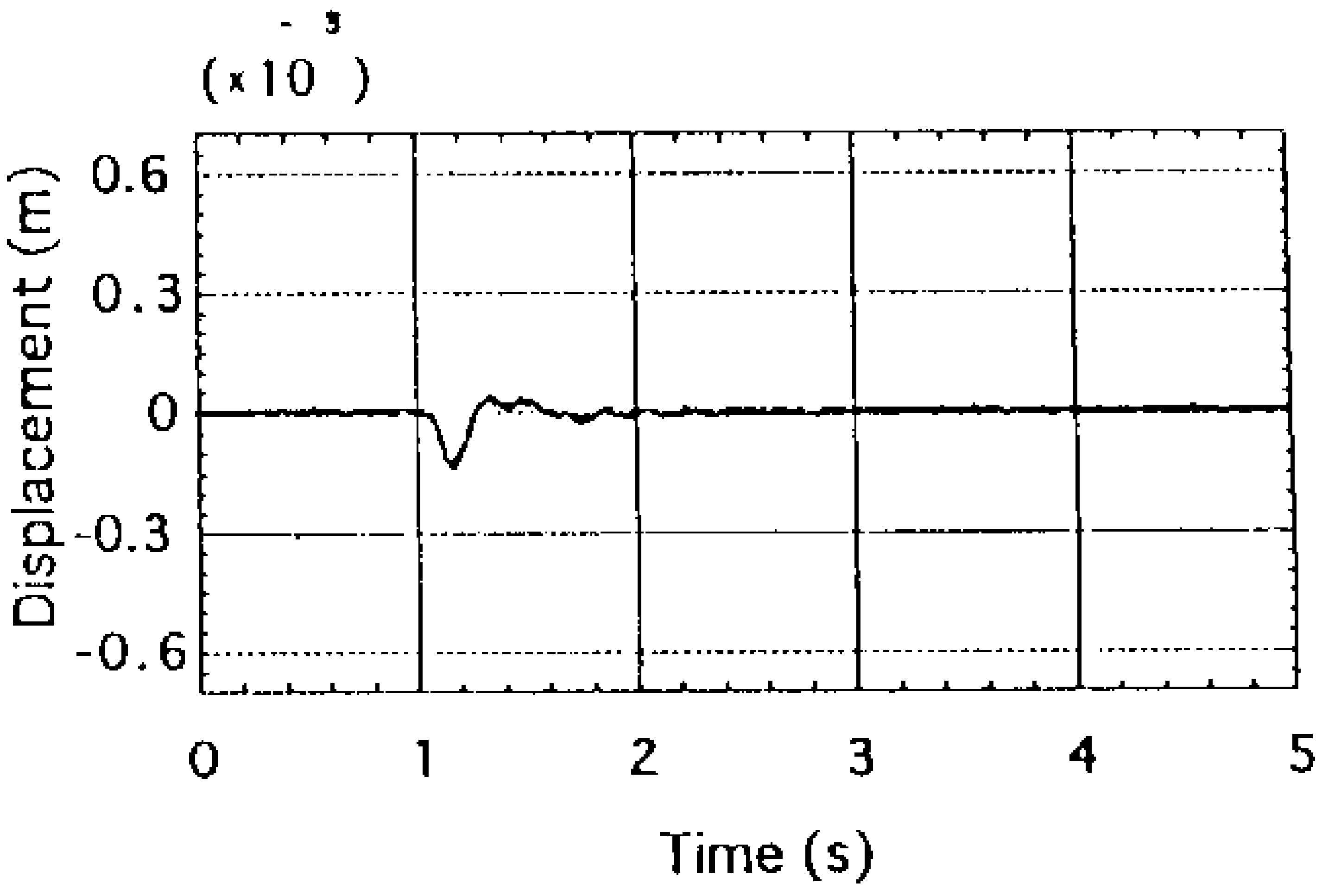


b) Without Upper Stator Magnet

Fig.16 : Vibration Characteristics of Rotor.

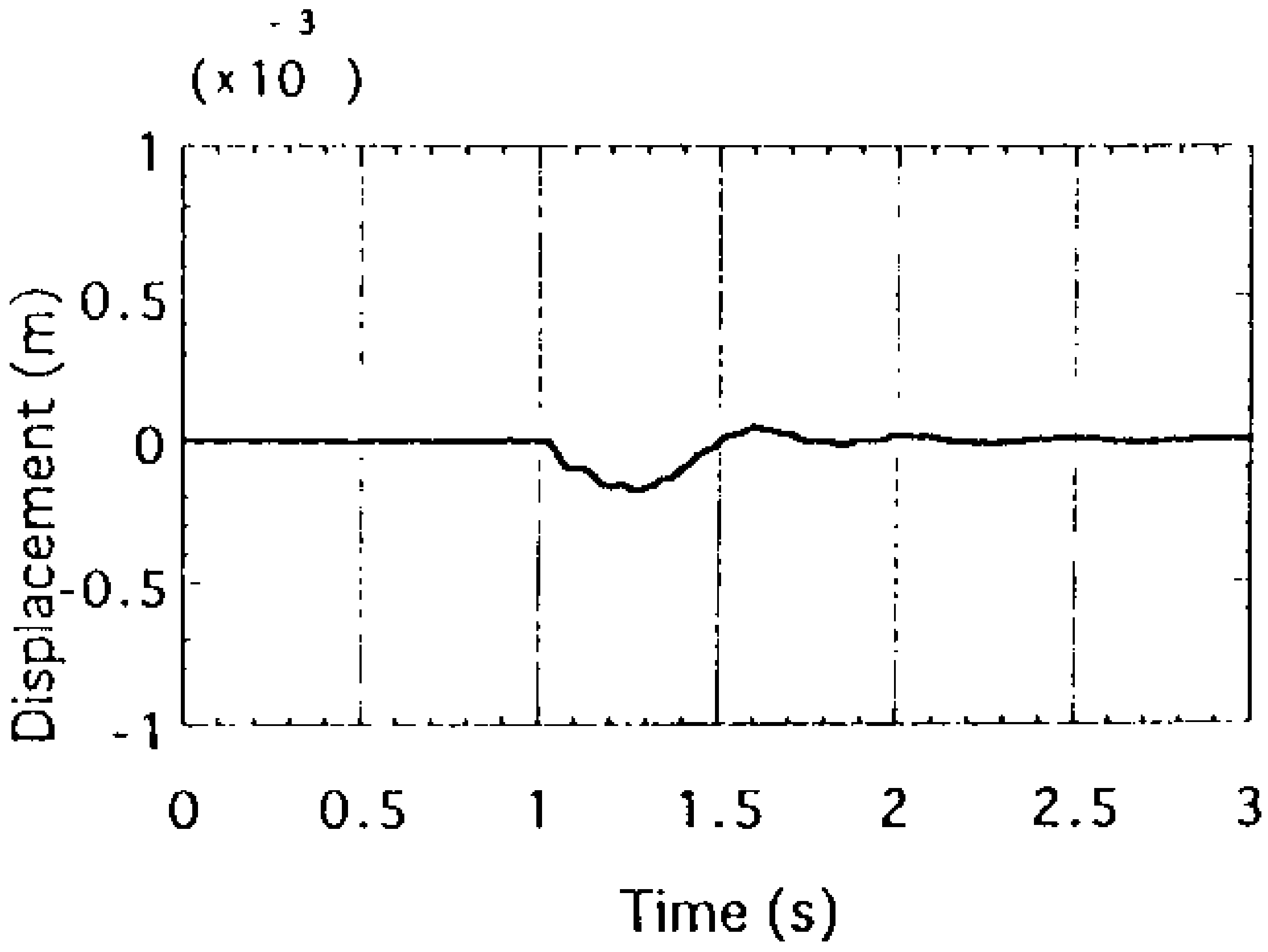


a) x-axis Vibration

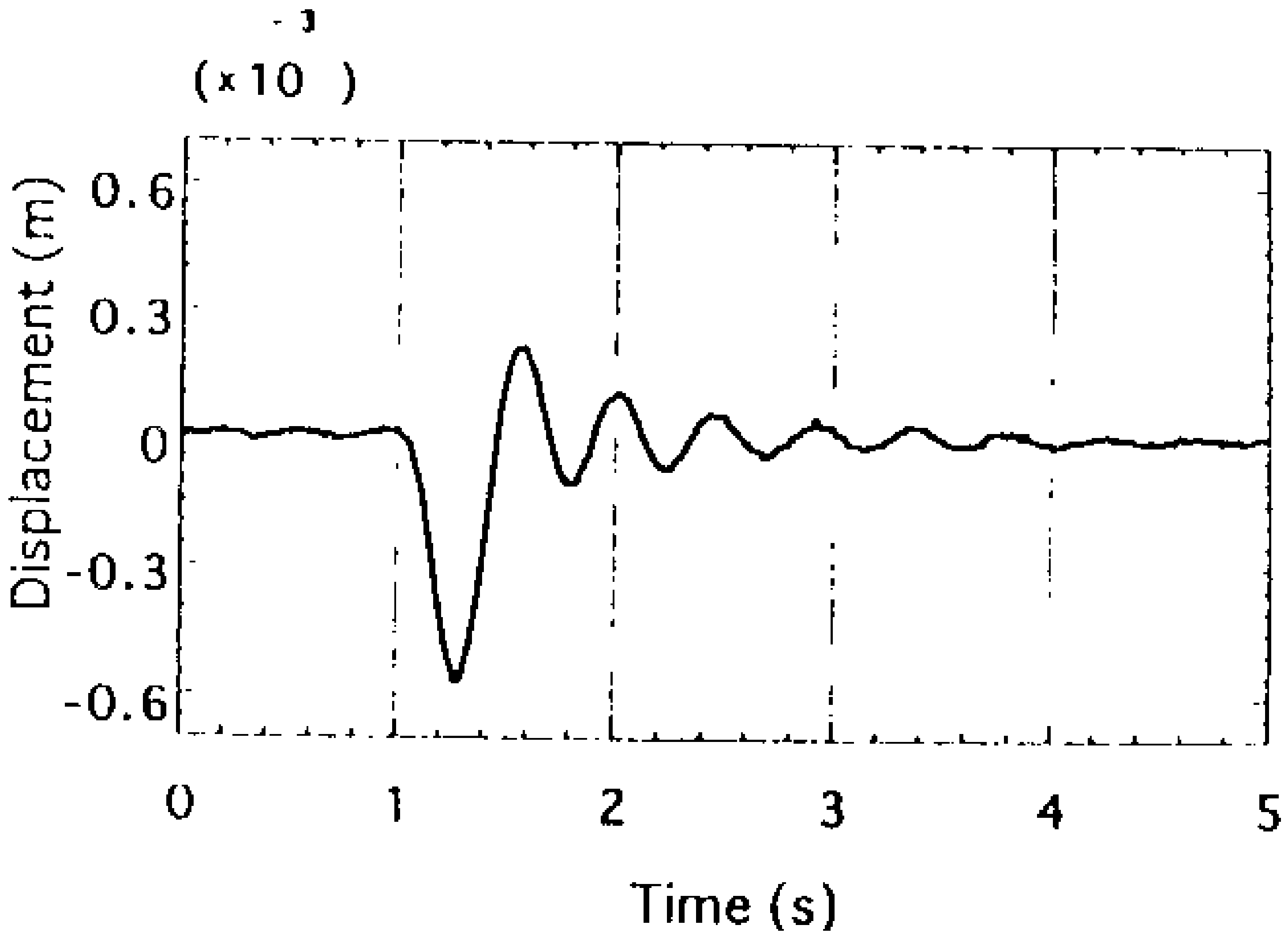


b) z-axis Vibration

Fig.17 : Disturbance Characteristics with Upper Stator Magnet



a) x-axis Vibration



b) z-axis Vibration

Fig.18 : Disturbance Characteristics without Upper Stator Magnet

7. Conclusion

This paper has investigated the configuration and placement of permanent magnet for disturbance attenuation and faster stabilization on repulsive type magnetic bearing and showed that by proper placement of permanent magnet in the bearing system, the stiffness characteristic can be improved 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 performances of two types of bearing model has been studied and their performances are compared. It can be concluded here as the effect of radial disturbance is less in the system having higher stiffness, it can operate with large radial disturbance force.

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