Development of repulsive type magnetic bearing - A review of permanent magnet configuration

著者	Mukhopadhyay S.C., Ohji T., Yamada Sotoshi
著者別表示	山田 外史
journal or publication title	Applications of Electrimagnetic Phenomena in Electrical and Mechanical Systems / Studies in Applied Electromagnetics and Mechanics
volume	15
page range	117-124
year	2005
URL	http://doi.org/10.24517/00049224

Applications of Electromagnetic Phenomena in Electrical and Mechanical Systems
D. Kacprzak, S.C.Mukhopadhyay and I. Tuleasca (eds.)

DEVELOPMENT OF REPULSIVE TYPE MAGNETIC BEARING - A REVIEW OF PERMANENT MAGNET CONFIGURATION

S. C. Mukhopadhyay, T.Ohji* and S. Yamada**
Institute of Information Sciences and Technology
Massey University, Private bag 11 222
Palmerston North, New Zealand
Email: S.C.Mukhopadhyay@massey.ac.nz
* Toyama University, Toyama, Japan
** Kanazawa University, Kanazawa, Japan

Abstract

Usually the rotor is levitated in the magnetic field created either by employing electromagnets or by using permanent magnets in magnetic bearing system. Utilizing the repulsive force between permanent magnets for levitating the rotor it is possible to reduce the number of electromagnets used in magnetic bearing system and the corresponding control circuit can be simplified. The configuration of permanent magnets depends on many factors such as type of machine in which it is used, the amount of weight to be levitated, the material characteristic of the magnet, and its availability etc. This paper has discussed different configuration of permanent magnets used in repulsive type magnetic bearing system. Some simulation and experimental results are presented.

1. INTRODUCTION

In magnetic bearing system the rotor is levitated in the magnetic field. The magnetic bearing system can be either of two types: (i) Active magnetic bearing in which all are electromagnets and (ii) Passive magnetic bearing in which a combination of electromagnets and permanent magnets (PM) are used. In repulsive type magnetic bearing system usually the rotor is levitated by the repulsive forces between stator and rotor permanent magnets. The system is unstable in nature. The controlled electromagnet is used to keep the rotor in the desired position. The repulsive magnetic bearing system has the advantages of using a smaller number of electromagnets and simplified control scheme compared to active magnetic bearing system. The advantages of using magnetic bearing system compared to mechanical bearing in high speed motors are long life, frictionless and lubrication free operation, feasible operation at high speed etc. Many research papers have been published on magnetic bearings using permanent magnets [1, 2]. But the satisfactory performance of this type magnetic bearing is strongly dependent on the characteristics of the permanent magnet and its configuration in the bearing system. Two repulsive magnetic bearing systems using permanent magnets for the levitation were fabricated a few years back [3, 4] and their levitation and control performance were compared [5]. Due to aging and/or as both the magnets are repelling each other, there will be demagnetization of the permanent magnet, resulting the field distribution along the magnet's periphery non-uniform and this will affect the performance of the bearing system [6].

II. BACKGROUND OF THE PROJECT

Two types of magnetic bearing systems were developed earlier. The fabricated model of the horizontal-shaft machine is shown in Fig. 1. The configuration of permanent magnets for this scheme is shown in Fig. 2. It is seen that a section of PM is used at the top of rotor PM. The upper section of the PM reduces the levitated force but improves the stiffness. Since the radial axis i.e. the vertical axis is uncontrolled one, a higher stiffness is desirable to reduce the effect of external radial disturbance. An optimum upper magnet section is required to achieve optimum performance of the baring system.

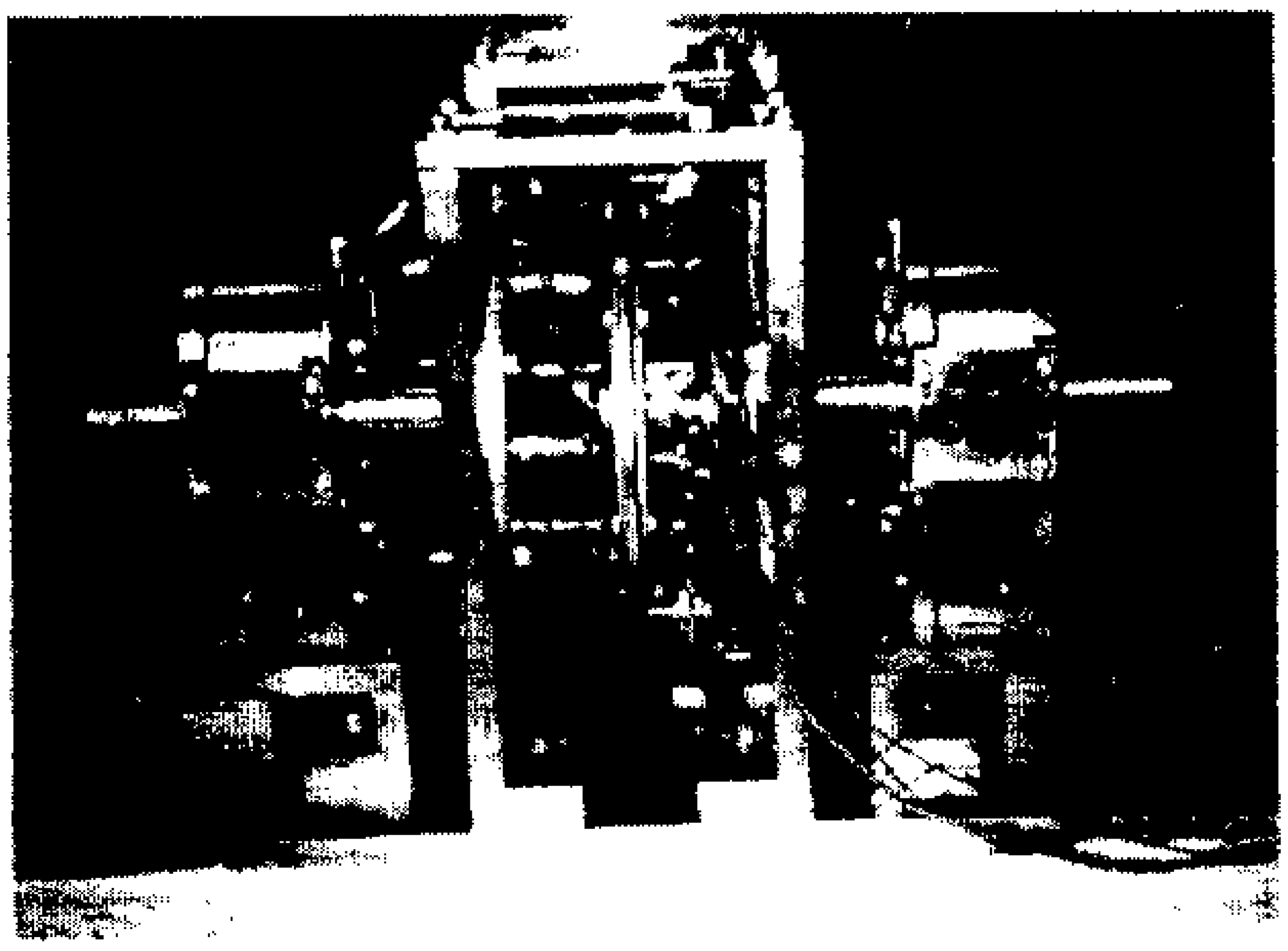

Fig. 1 Fabricated magnetic bearing system for horizontal shaft machine

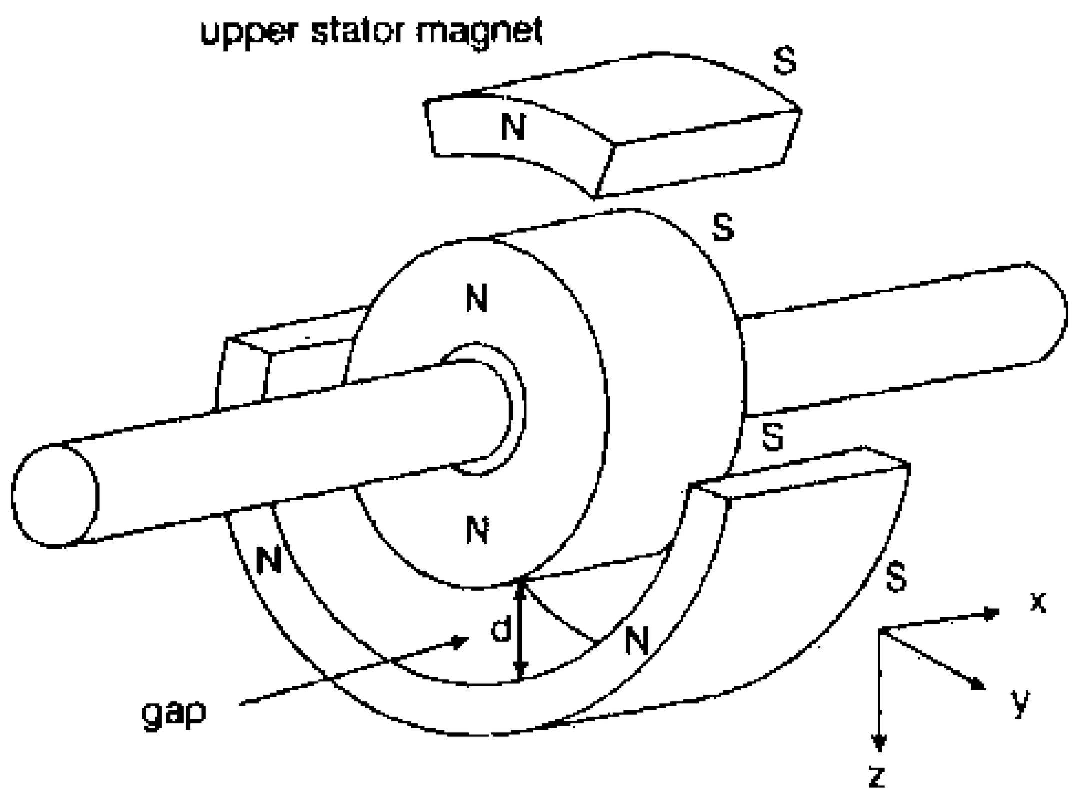

Fig. 2 The configuration of PM

Fig. 3 shows a two-dimensional view of the magnet assembly. The upper section of the magnet as shown by the arc angle θ, is decided from the finite element analysis. The field analysis has been carried out for different values of θ and the forces and stiffnesses are calculated for various values of d. Figs 4 and 5 show the variation of repulsive force and Z-axis stiffness as a function of gap distance, d. It is seen that with increase value of θ the repulsive forces is becoming less but the stiffness is getting improved initially. Since the repulsive force is very important to levitate the rotor, a desirable value of θ of 45° is chosen to fabricate the system.

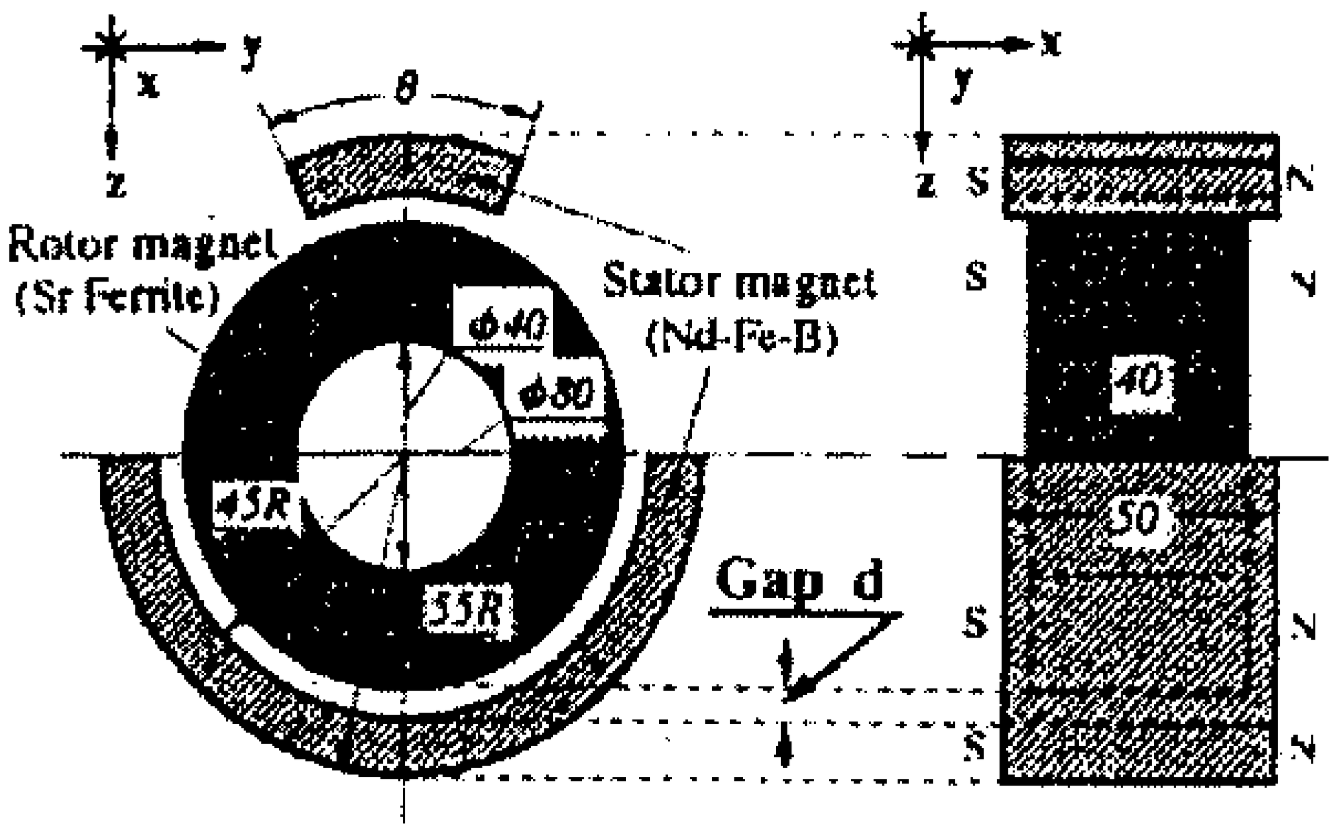

Fig. 3 2-D view of the magnet assembly

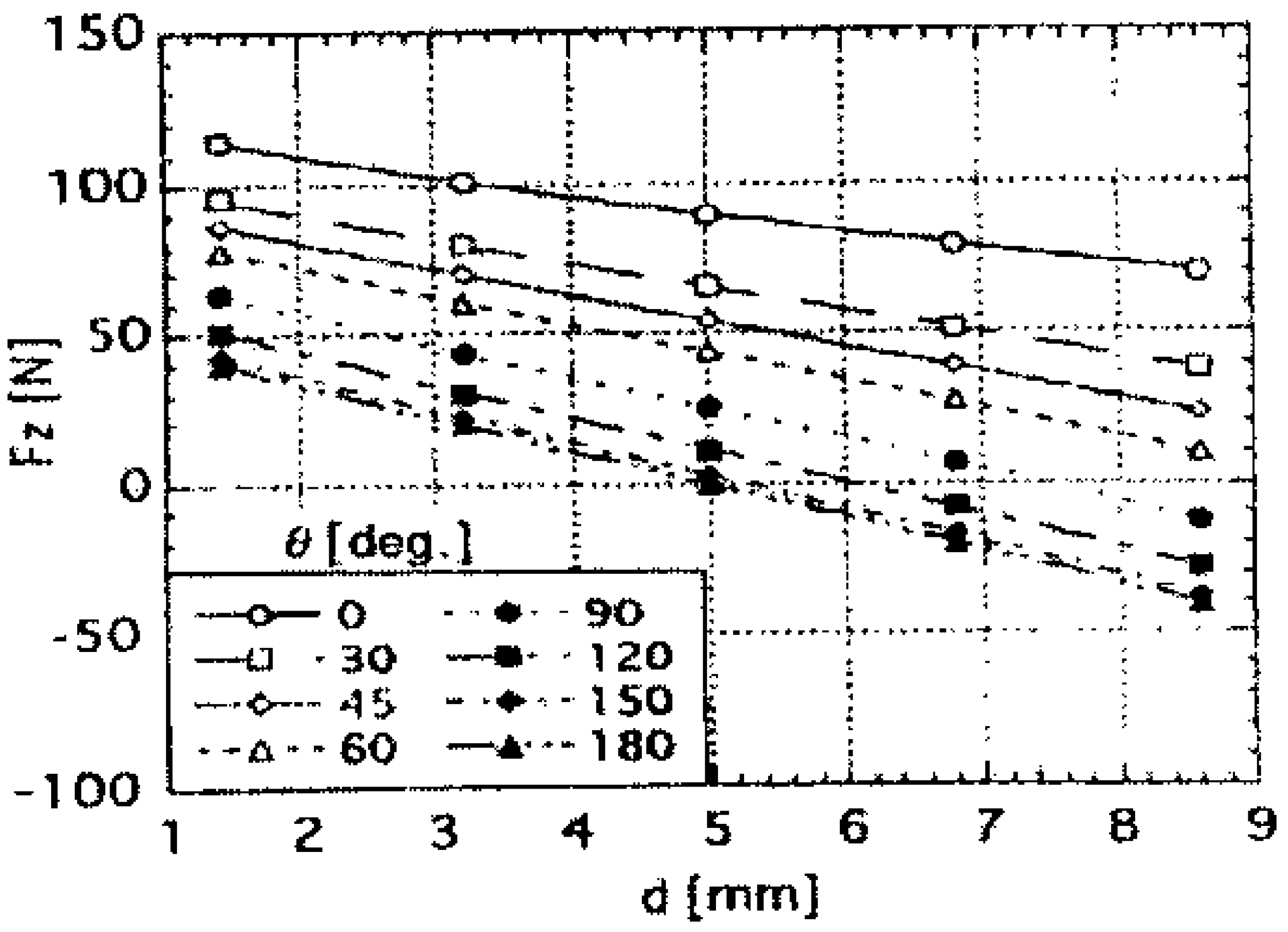

Fig. 4 Variation of repulsive force with gap distance

The repulsive type magnetic bearing system for the vertical shaft machine is shown in Fig. 6 and it was fabricated a few years back. The magnet used for the system was of circular configuration as shown in Fig. 7. This type of bearing system is stable along the radial direction but is unstable along the vertical axis.

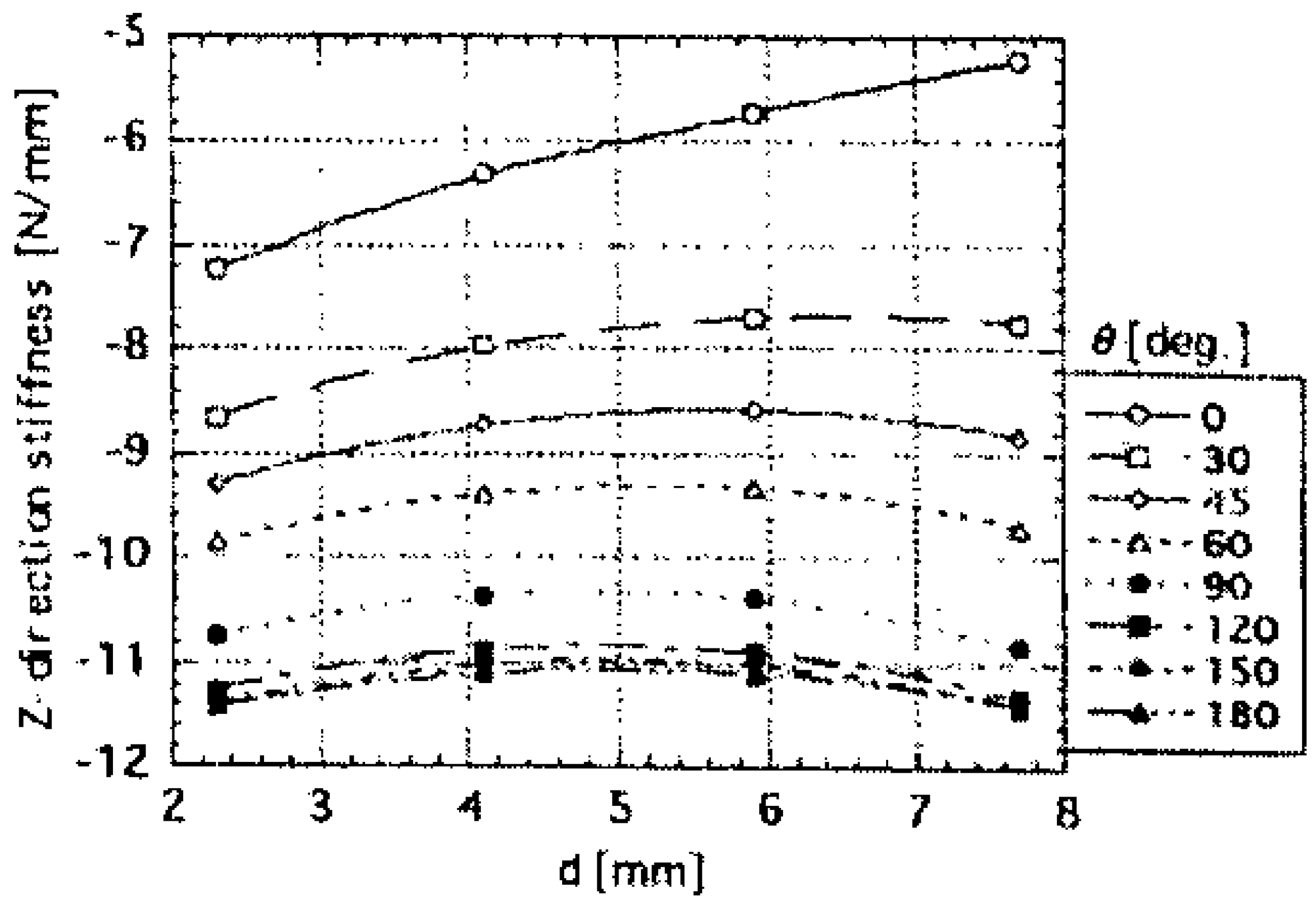

Fig. 5 Variation of stiffness with gap distance

After around five years of operation the flux density distribution of the magnets for this system became non-uniform which has affected its performance. The different remedial measures were reported in [6] but the best option is to replace the permanent magnets which is a costly solution.

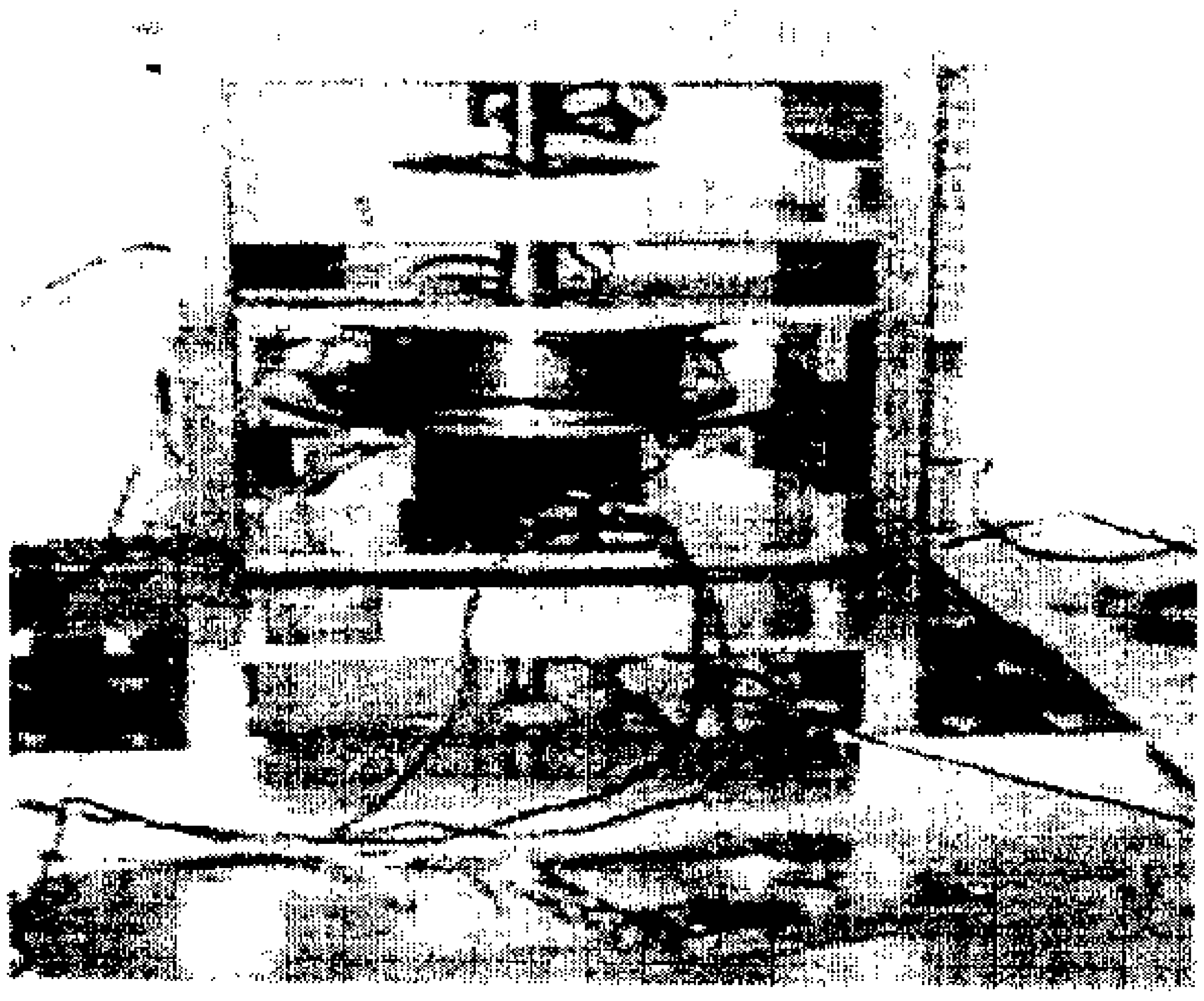

Fig. 6 Fabricated magnetic bearing system for vertical shaft machine

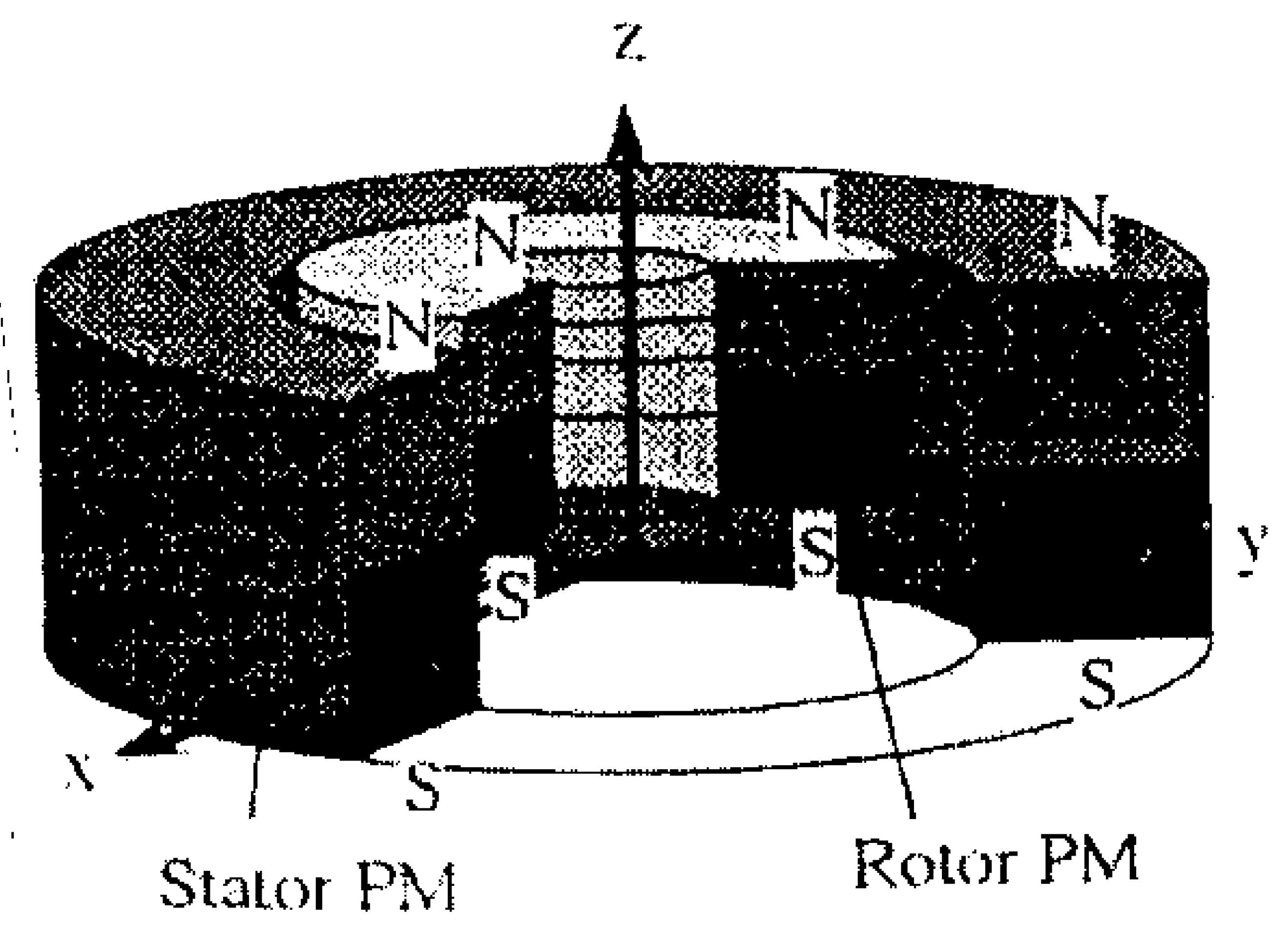

Fig. 7 The PM configuration for vertical-shaft machine

In this project we aim to fabricate a repulsive type magnetic bearing system for vertical shaft machine using an alternative magnet configuration which will be of cheaper option compared to the earlier model. Instead of using big circular magnets many small circular permanent magnets are used which are arranged along the periphery of a circular disc. Two such discs are used, one of which is fixed to the stator and the other one is fixed to the rotor shaft. They form a magnetic bearing. Two such bearings are used to levitate the rotor.

3. DESIGN CRITERION

The thickness and number of magnets and their arrangements is a matter of interest from stability consideration. An analytical model has been done to characterize the forces along three axes. So the selection of magnet thickness and the gap between the disks to be selected based on some criterion. The outer diameter of the bearing disk is kept same to that of the outer diameter of the motor. Initially the distance of the center of the magnets from the disk center is 50 mm is chosen for stator disk and that of rotor disk is 47.5 mm as shown in Fig. 8. In this scheme 24 magnets are used in both the rotor and stator disk. Table 1 shows the details of the magnet used in the system.

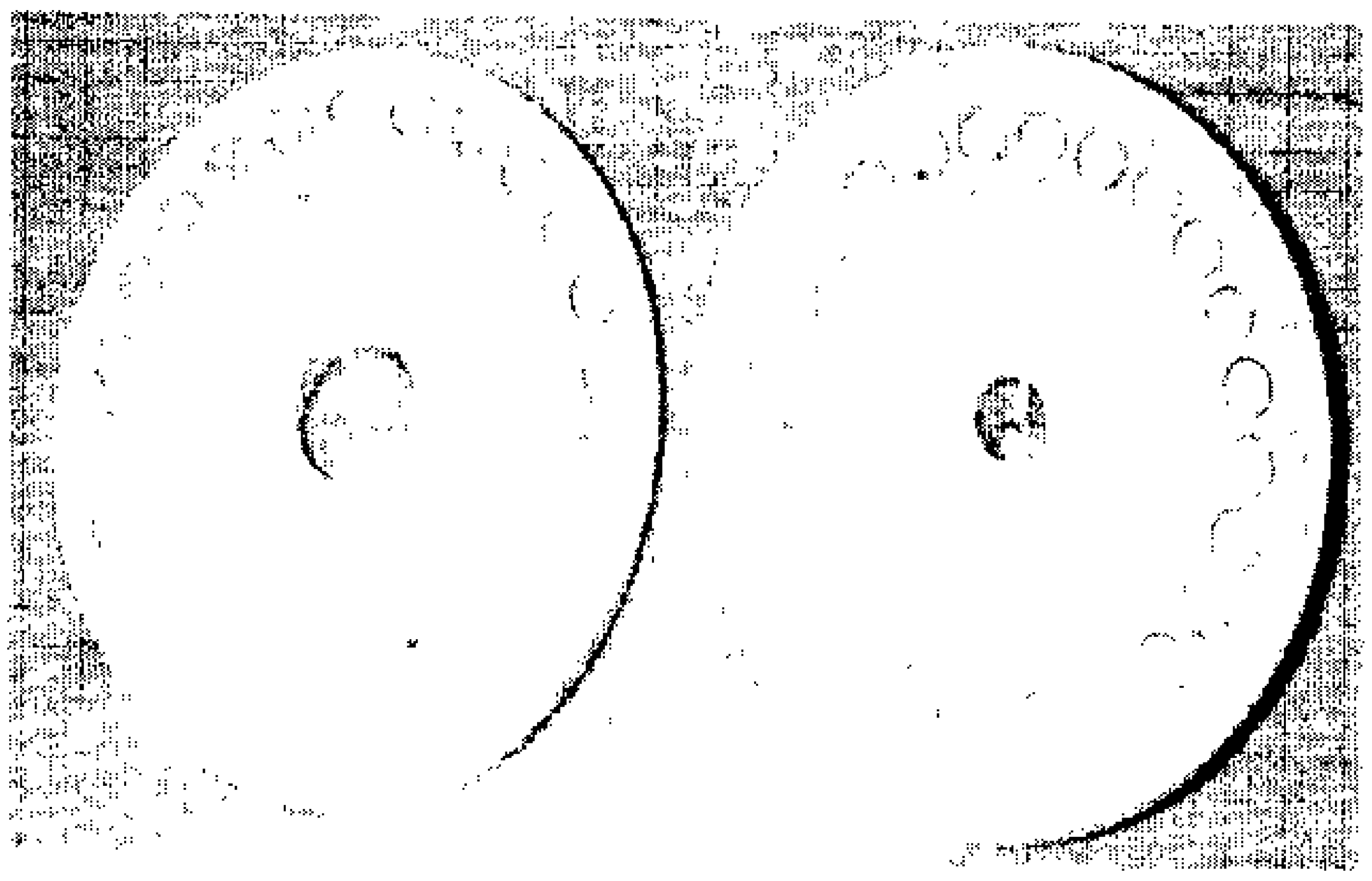

Fig. 8 A prototype fabricated magnetic bearing with 24 magnets both in stator and rotor disk

Table 1 Specifications of magnet

Make	The Magnet Source, USA
Part number	Neodymium 27H
Size	Dia = 0.375" and Thickness = 0.1"
Residual flux density	1.08 T
Coercive force	0.779 X 10^6 A/m

The schematic arrangement of the permanent magnets in two-dimension and the forces are shown in Fig. 9. The analytical expression of force between two magnet pole of intensity Q_{m1} and Q_{m2} is given by (1)

$$F = \frac{\mu_0 Q_{m1} Q_{m2}}{4\pi r_{12}^2} u_{12} \quad (1)$$

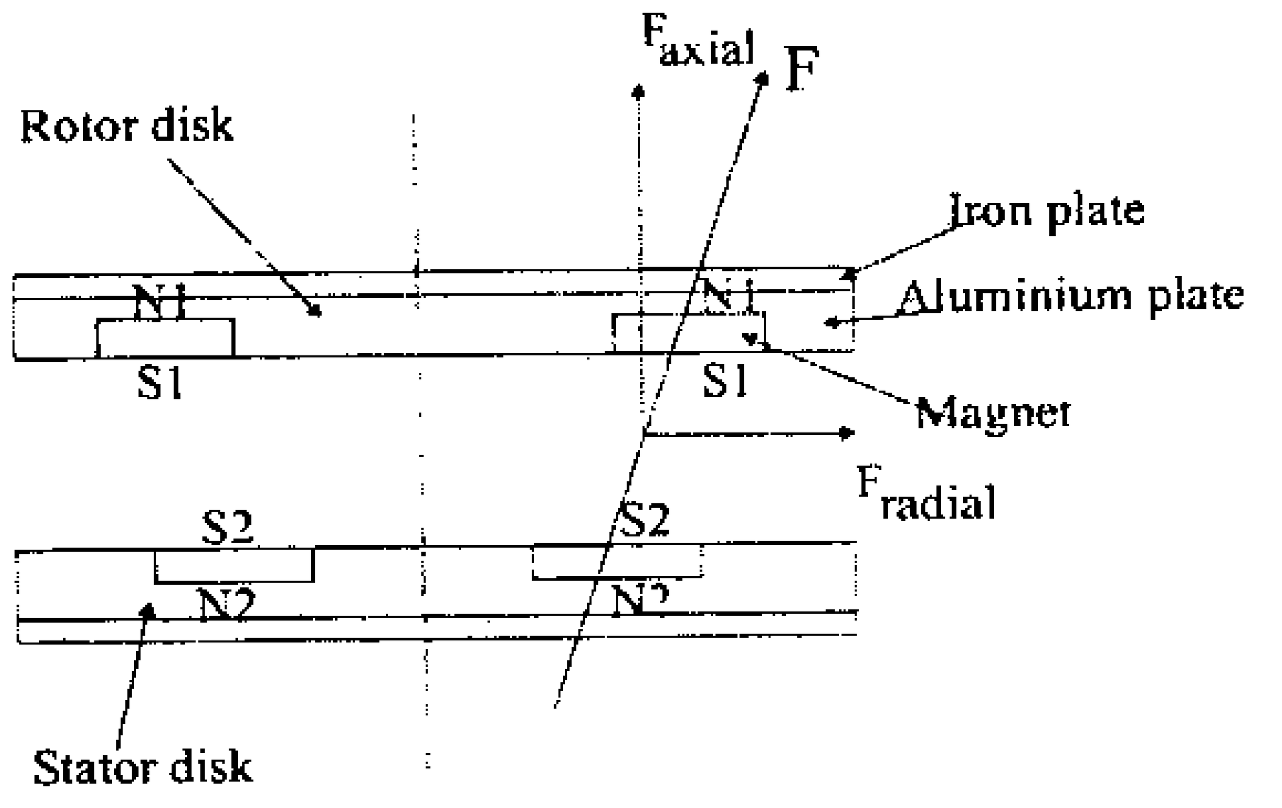

Fig. 9 Schematic representation of bearing to show the different forces

in which the intensity Q_m is given by $Q_m = H_C A$; H_c is the coercive force and A is the pole face area. It is assumed here that the pole intensity of the magnet is concentrated at the center of the magnet. The unit vector u_{12} is directed along the line joining Q_{m1} and Q_{m2}. There are four forces acting between two magnets as shown in Fig. 9. F_{N1S2} and F_{N2S1} are the attractive forces and F_{N1N2} and F_{S1S2} are the repulsive forces. The resultant force is given by the vector sum of all the forces.

Fig. 10 shows the force characteristic as a function of gap distance between the two disks for different magnet thickness of the model as shown in Fig. 8. It is seen that the repulsive force between the disks appears when the gap between them is becoming large than that of a certain value. Below that gap the force acting between the set of magnets is becoming attractive. Since the magnets are used to levitate the rotor it is very important that the nature of the force must be repulsive. So the selection of magnet thickness and the gap between the disks to be selected based on some criterion.

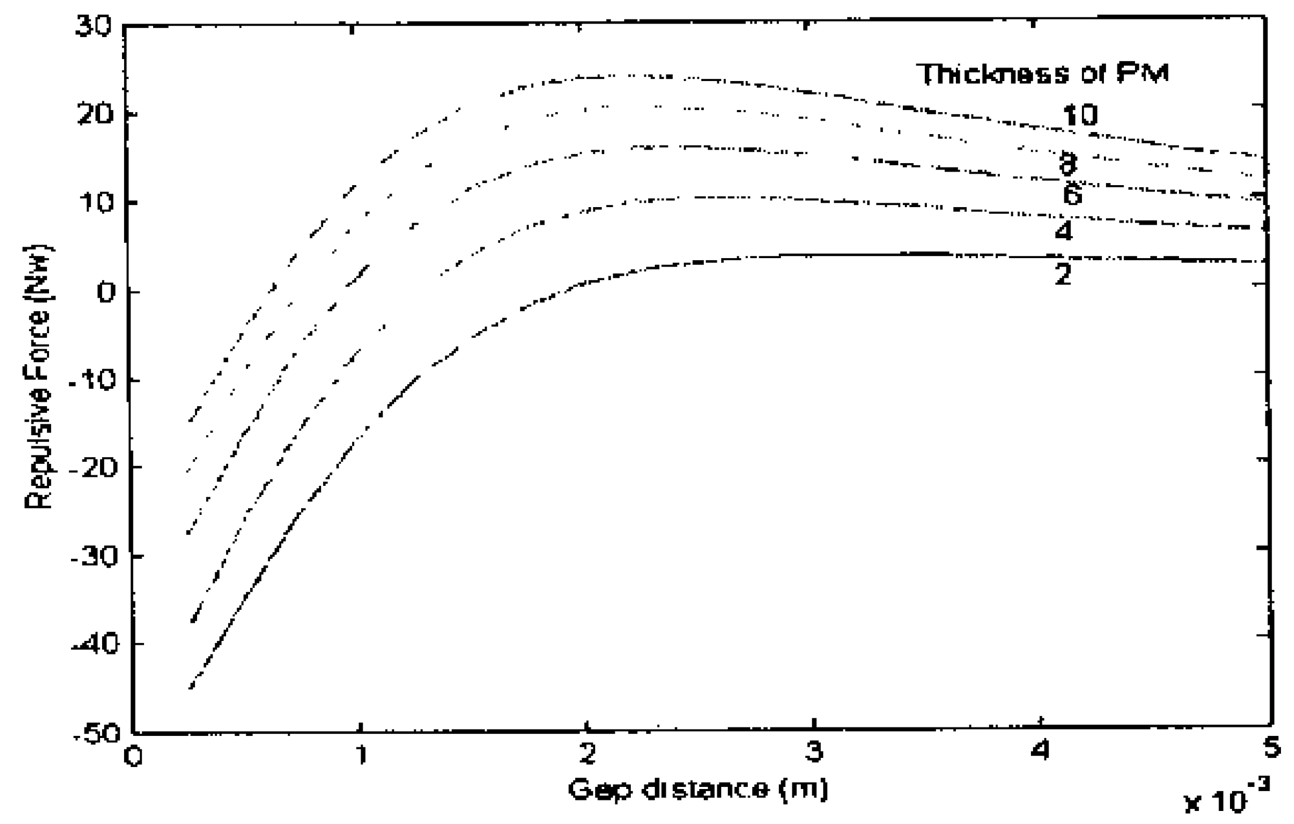

Fig. 10 Variation of repulsive force with gap distance for different PM thickness

The distance of the center of the magnets from the disk center is 50 mm for stator disk and that of rotor disk is 47.5 mm. The selection of this parameter is explained in Fig. 11. If there is a displacement of 1 mm along the radial axis, the rotor will come back to the original central position for 47.5 mm while the other cases it will go to one extreme side.

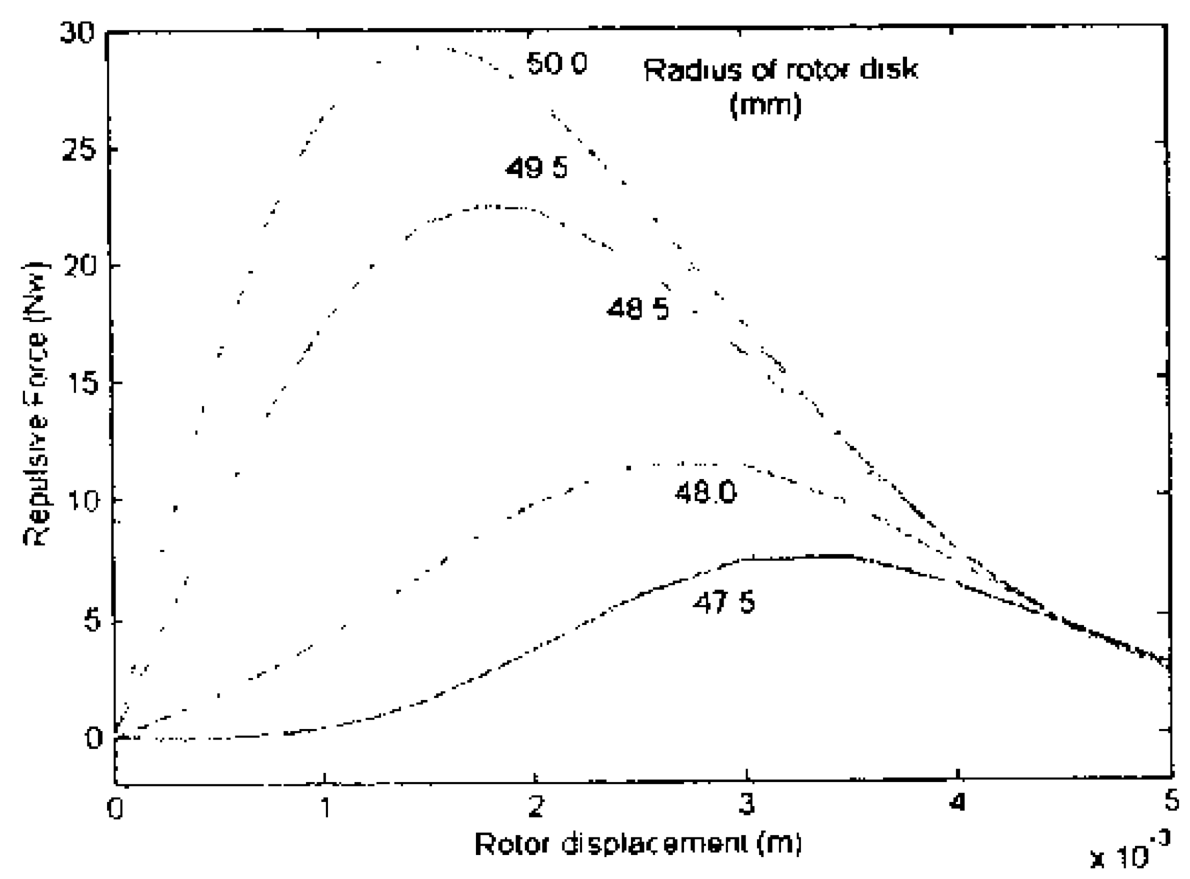

Fig. 11 Variation of repulsive force with radial displacement

The repulsive force varies considerably when the rotor rotates around its axis. Fig. 12 shows the variation of repulsive force as a function of rotation of the rotor for two different radius of rotor disk. Even though the radius of rotor permanent magnet of the fabricated system is 47.5 mm, it is seen from Fig. 12 that there is a considerable change of force. This will behave as a ripple torque during the normal running condition of the rotor.

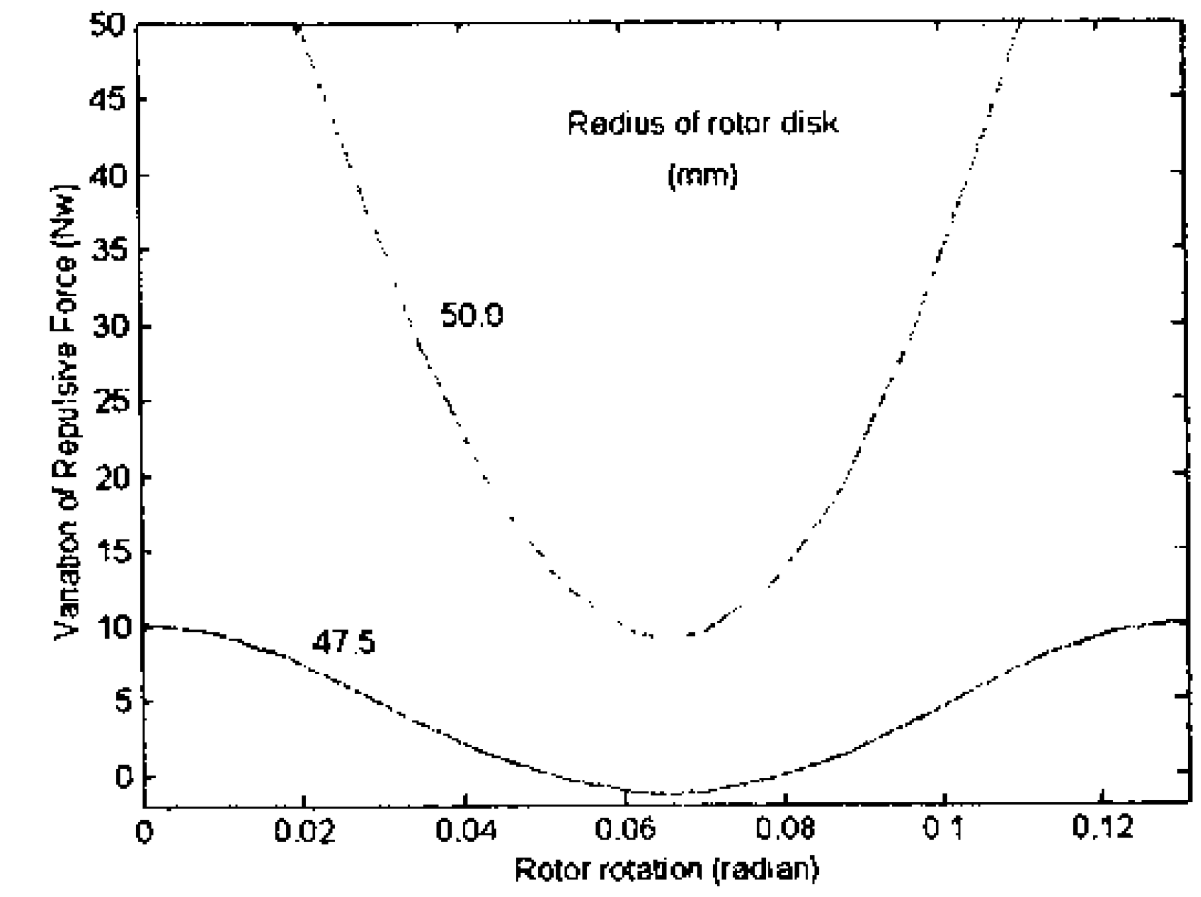

Fig. 12 Variation of repulsive force with the rotation of rotor

4. SYSTEM CONFIGURATION

In order to reduce the gravity of the above problem another set of permanent magnets is decided to be placed on the stator disk at a radius of 40 mm and is displaced by half pitch (7.5°) to that of other. The radius of the rotor disk is changed to 45 mm. The force characteristics are simulated using the analytical model described before and is shown in Fig. 13. It is seen that the variation of the force with the rotation of the rotor is negligible. It is possible to make almost zero variation of force with the rotation of the rotor by placing the two sets (upper and lower) of bearing with an angular shift of 3.75° between them. Based on this idea another model has been fabricated and the new fabricated system is shown in Fig. 14.

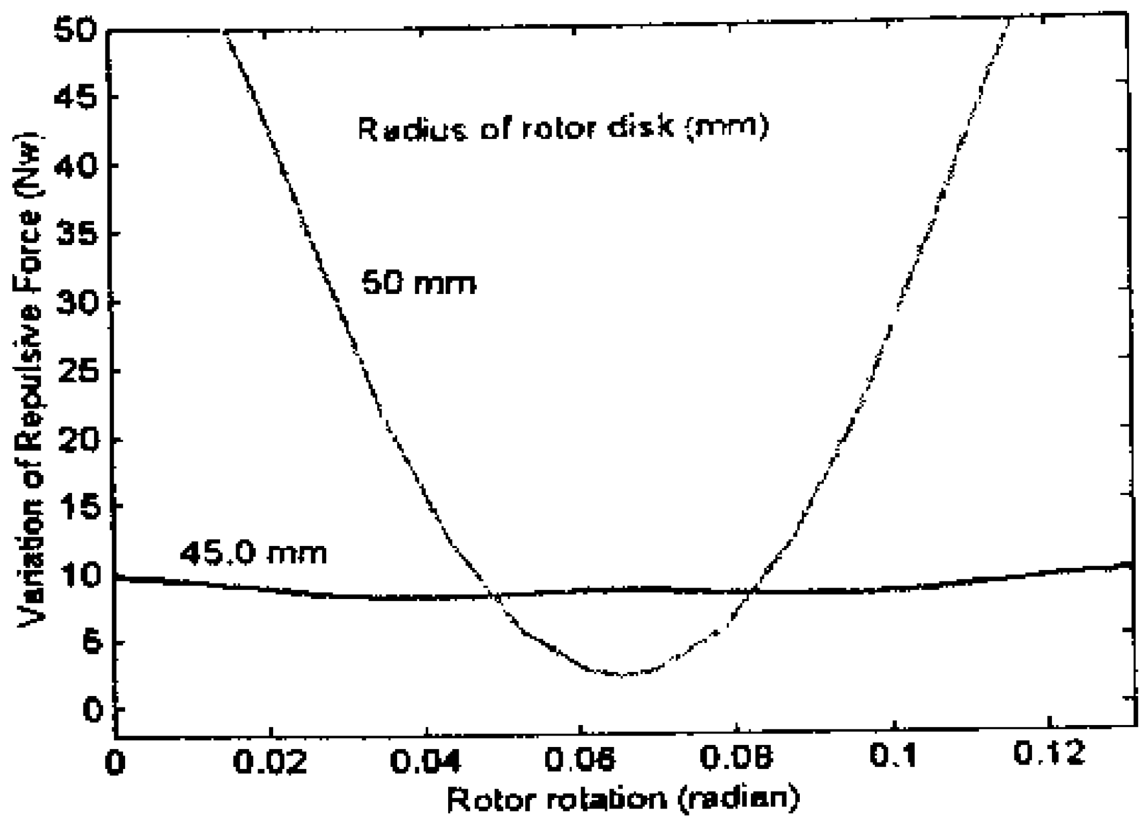

Fig. 13 Variation of repulsive force with rotor movement

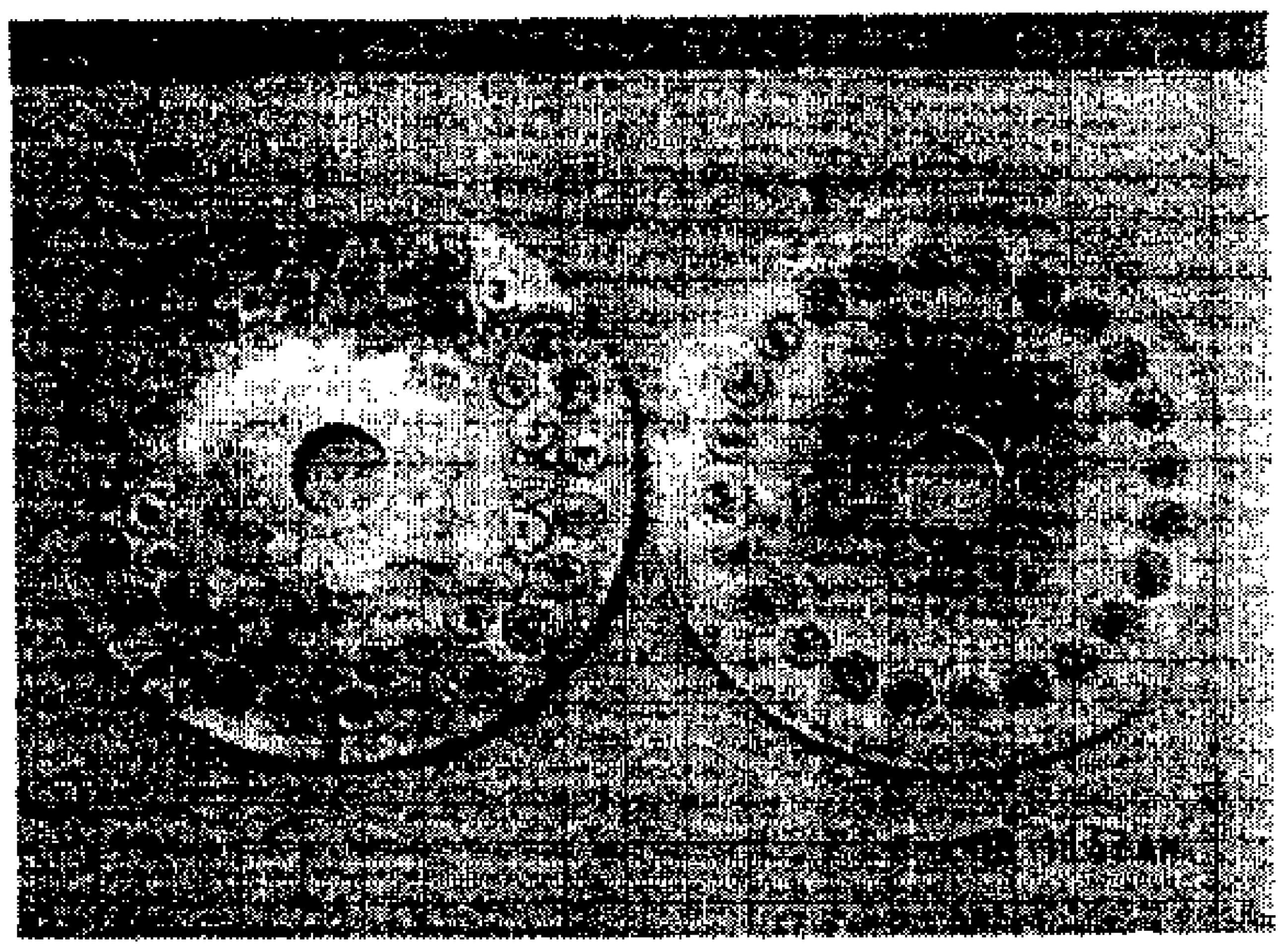

Fig. 14 The new fabricated model

The use of high electrical conductivity aluminum as base material has been thoroughly checked as it may produce appreciable amount of eddy current loss during high speed running condition. The flux distribution due to the worst situation of the permanent magnet has been analyzed using finite element method. Figs. 15 and 16 show the distribution of magnetic vector potential and the flux density of the closest orientation of the permanent magnets. It is seen that the magnitude of the flux density is too less to produce any loss in the aluminum disk used for holding the permanent magnets.

5. EXPERIMENTAL SET-UP AND RESULTS

In order to measured the acting repulsive forces between the two sets of disk and to

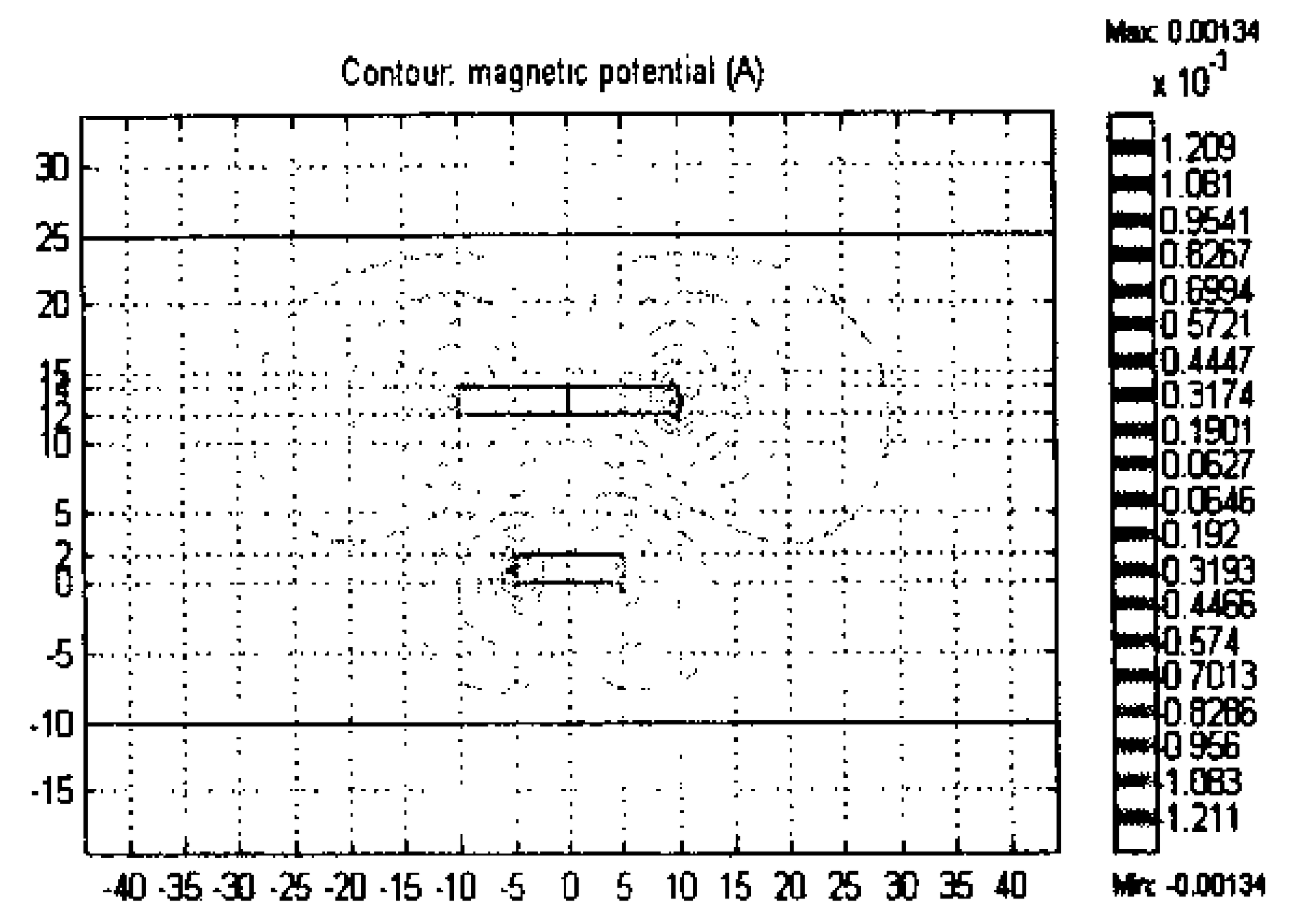

Fig. 15 The magnetic vector potential

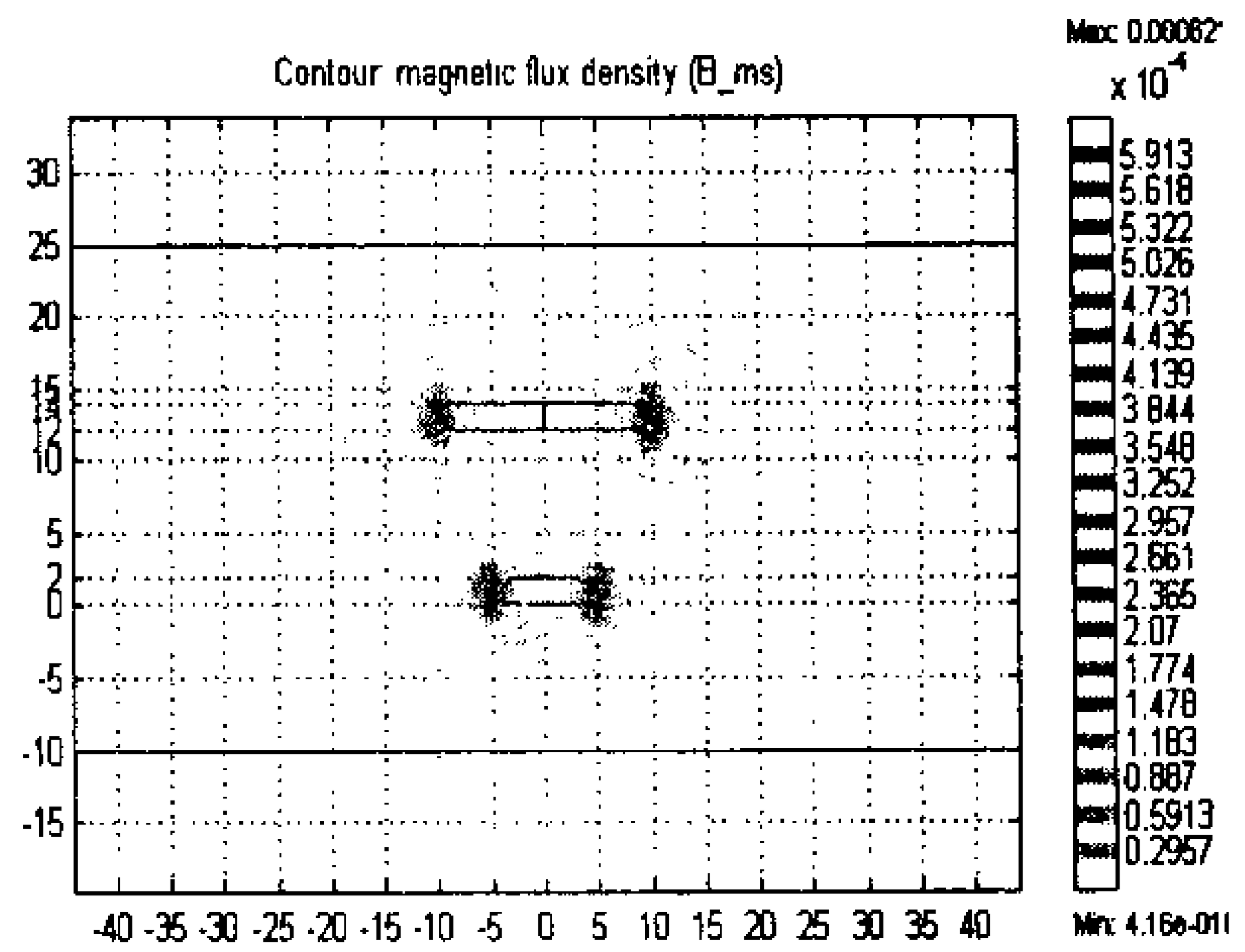

Fig. 16 The flux density distribution

confirm that the forces are sufficient to levitate the rotor of the motor, the repulsive force has been measured with the help of a force measuring instrument, make JJ Instruments, England which is available at Massey University. The two disks are fixed as shown in Fig. 17. The instrument is set to measure the repulsive force only. The complete instrument is shown in Fig. 18.

Fig. 19 shows the measured repulsive force characteristics as a function of the gap distance. It is seen if the gap between the disks becomes less than 16.8 mm the repulsive force acting between them changes its polarity and becomes attractive. This is one important finding and is very useful for the fabrication of the complete set-up.

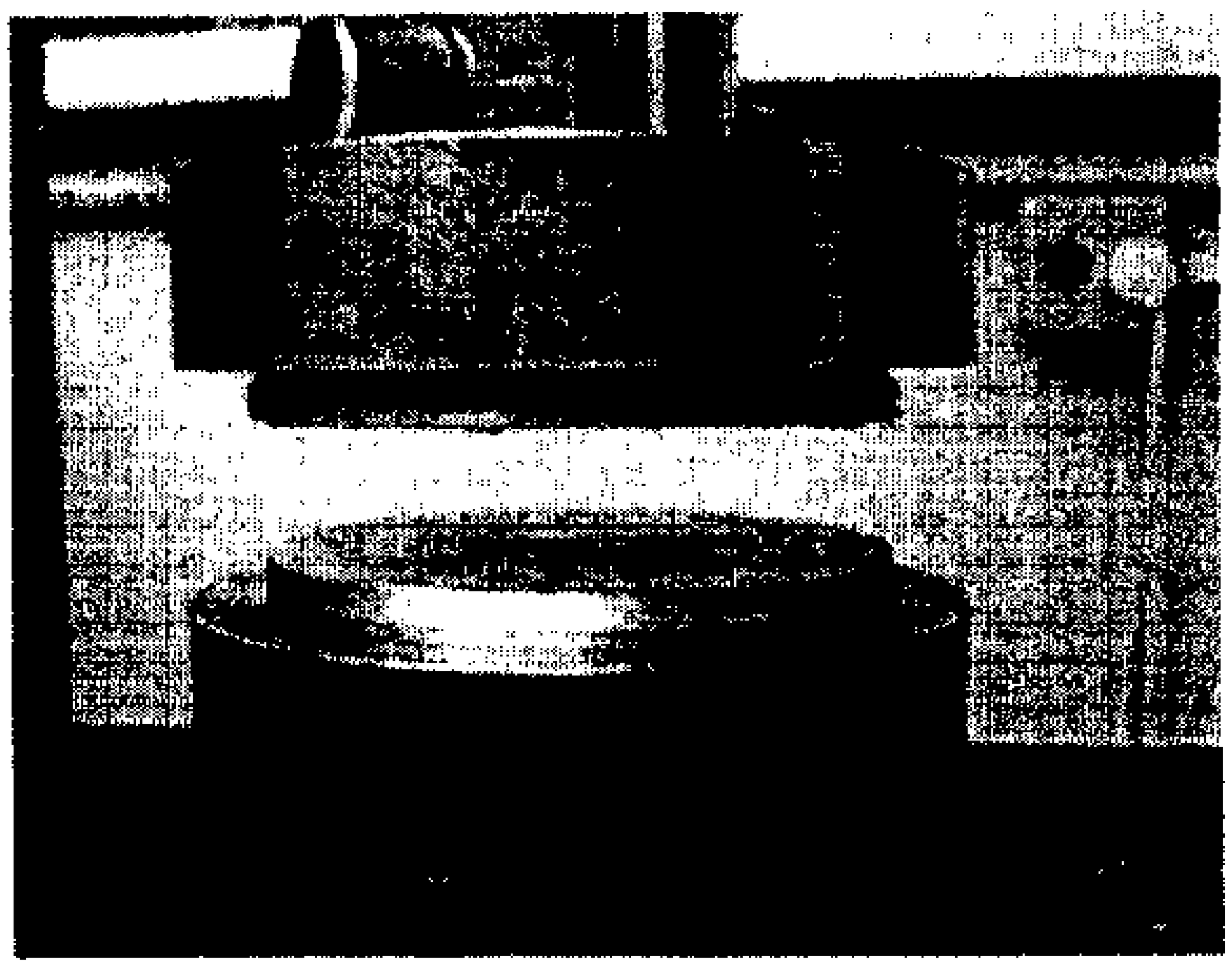

Fig. 17 The measurement of repulsive force

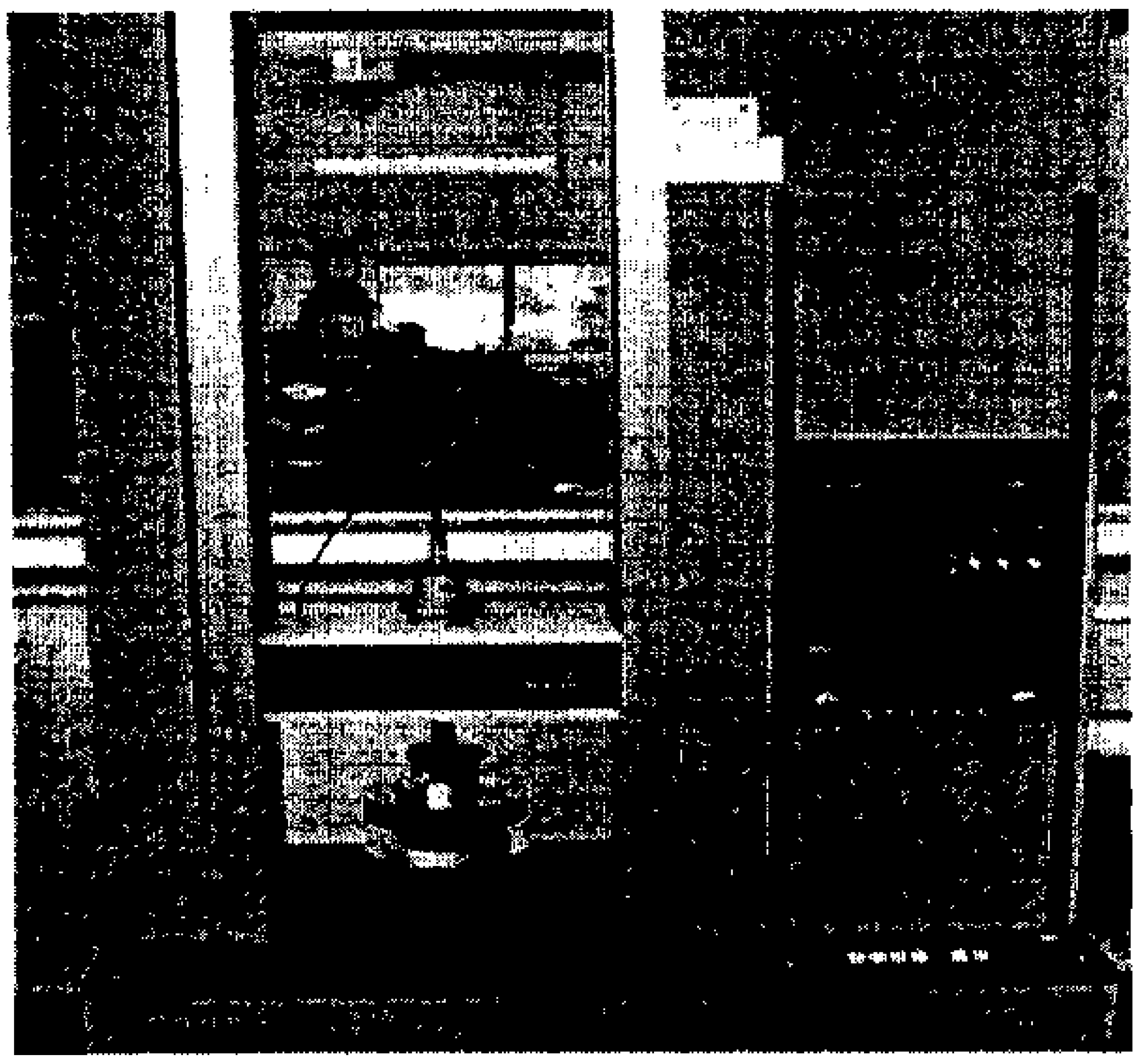

Fig. 18 The experimental set-up for the measurement of repulsive force

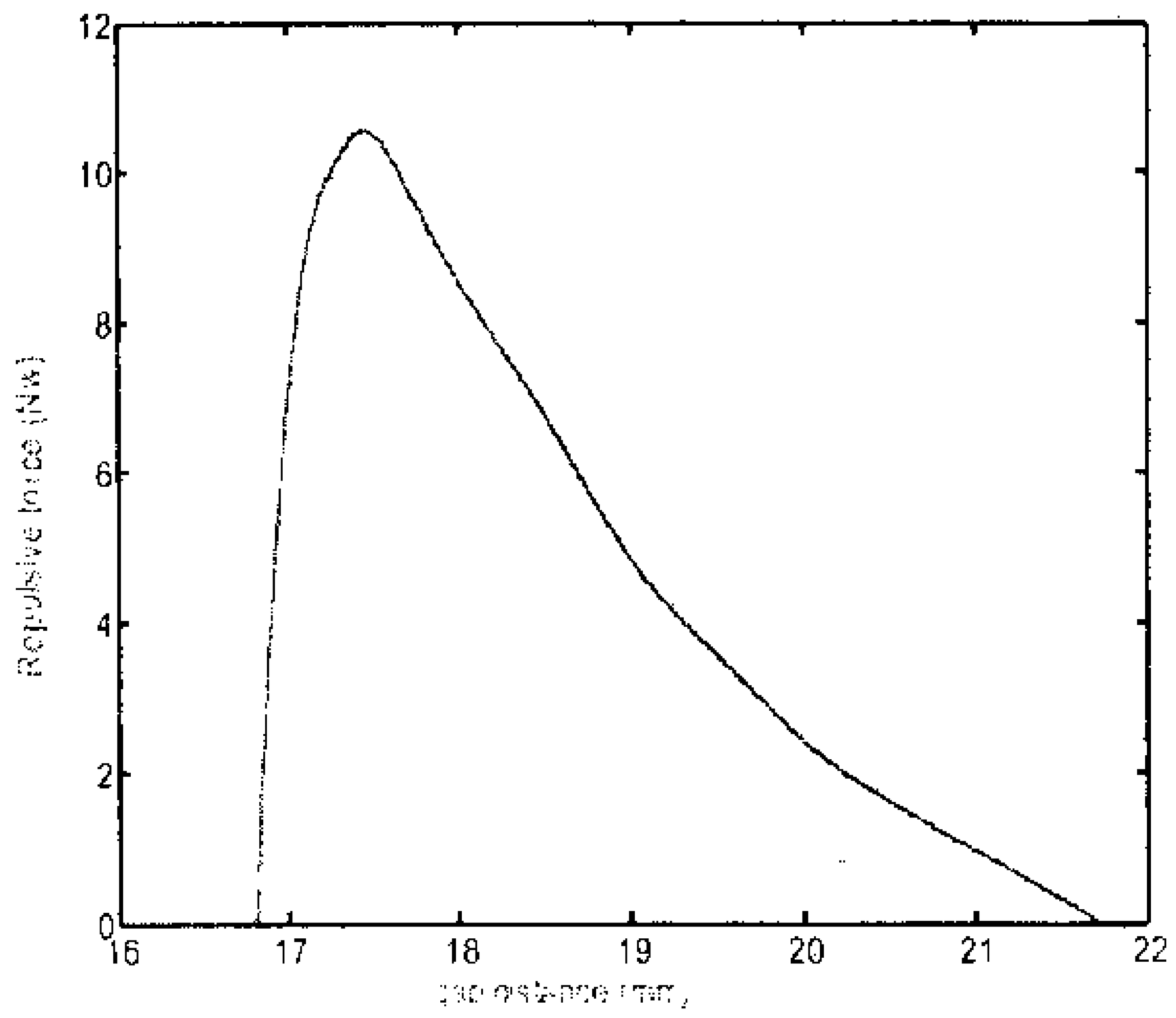

Fig. 19 The experimental variation of repulsive force with gap distance

The two disks are used to form a bearing and the upper one is shown on Fig. 20. Based on the magnetic bearing as shown in Fig. 20 the complete system has been fabricated and is shown in Fig. 21. The system is unstable along the vertical direction. A controlled electromagnet has been used for controlling the rotor position along this axis. This type of magnetic bearing system is stable along the radial axis but is unstable along the vertical direction. In order to maintain the desired position a gap sensor is used as shown at the top of Fig. 20 to derive the original gap. The gap signal is used in the control circuit to send some current to the electromagnet.

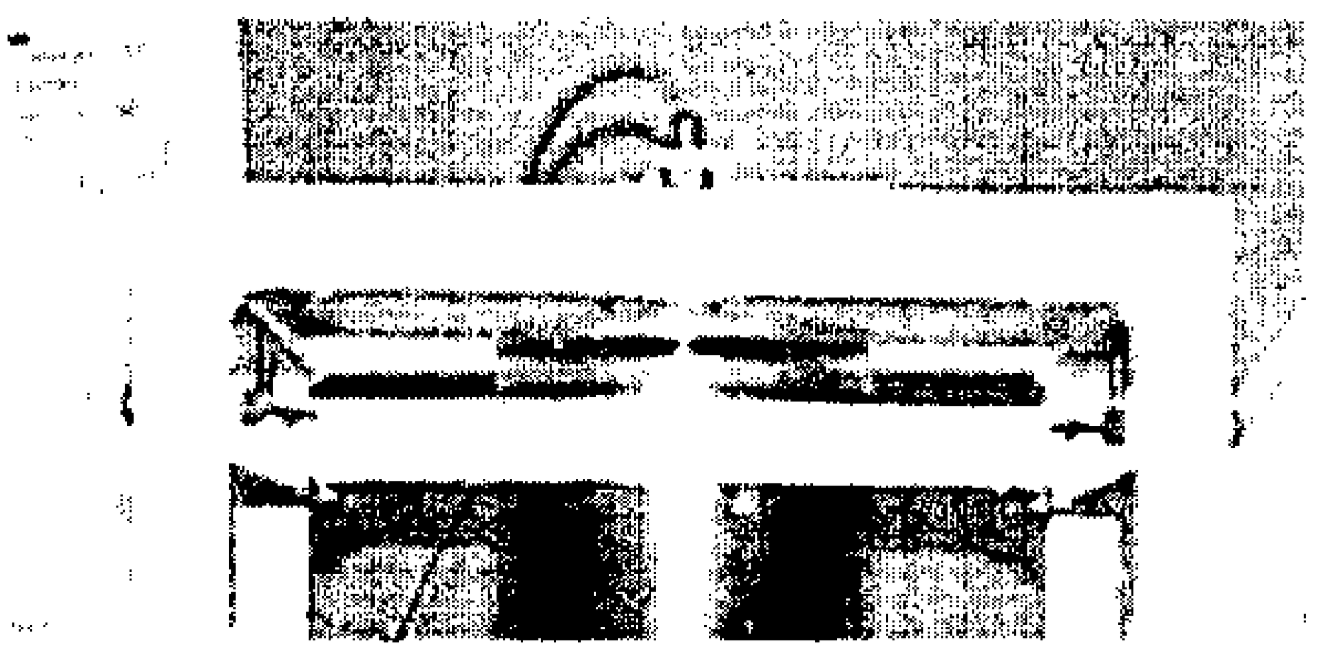

Fig. 20 Fabricated upper magnetic bearing

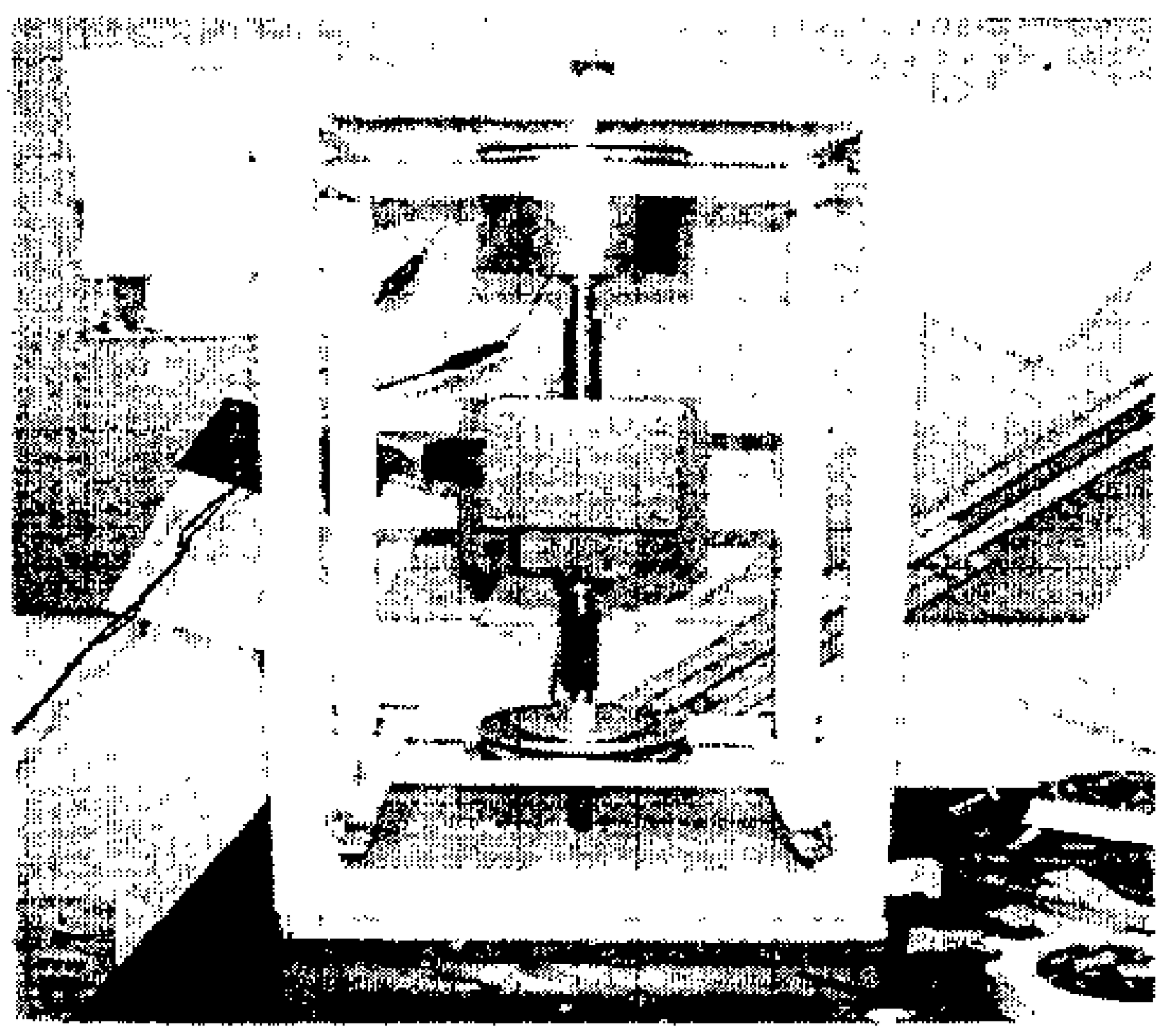

Fig. 21 The levitated magnetic bearing system

An analog PID controller has been implemented for the stable positioning of the rotor. Agilent make 6554A (60 V, 9A) DC power supply with the analog programming of output voltage and current facility has been used to supply the current to the electromagnet. In the absence of the current in the electromagnet the rotor rests on the stopper. While the current is passed through the electromagnet the rotor is lifted and maintained at the desired position as shown in Fig. 22. The peak to peak disturbance is less than ten micrometer as shown in Fig. 23. The bottom waveform shows the signal from the gap sensor while the top waveform corresponds to the signal to the input of the power supply.

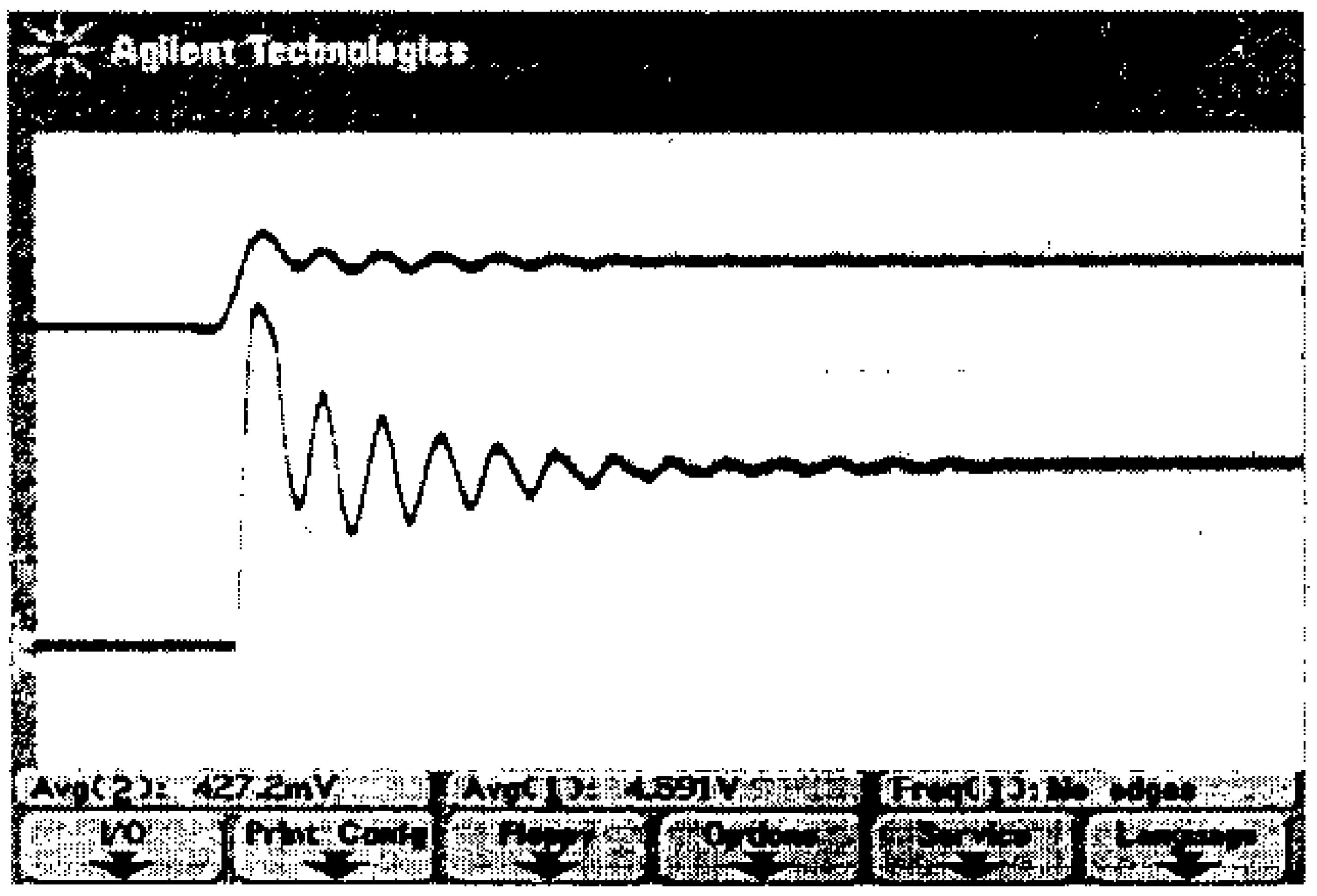

Fig. 22 The starting and positioning of the rotor

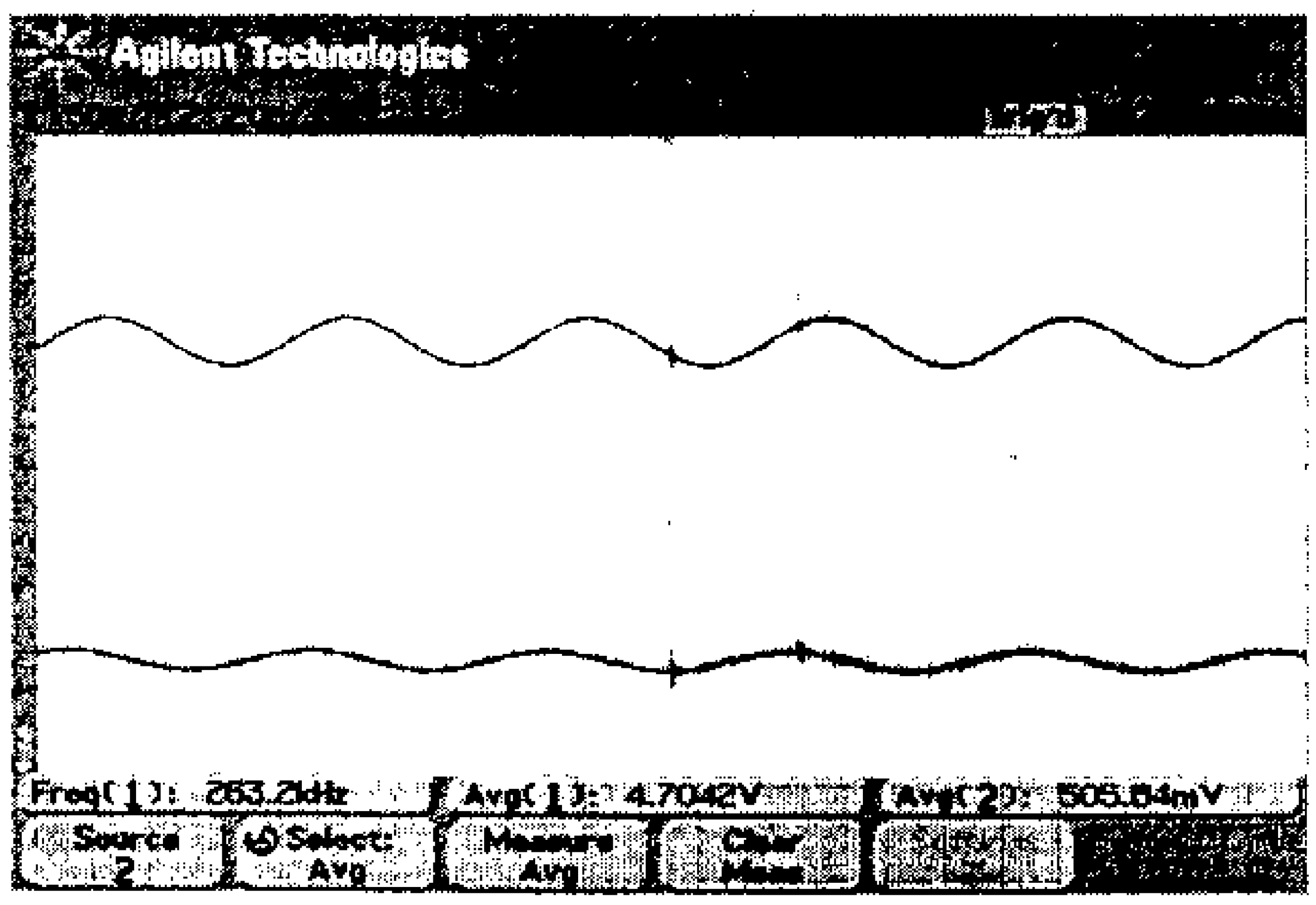

Fig. 23 Peak to peak vibration of the rotor

6. CONCLUSION

This paper has described different configurations of permanent magnets to develop repulsive type magnetic bearing. A prototype model of a repulsive type magnetic bearing system using a novel arrangement of permanent magnets has been fabricated. Our aim is to make this magnetic bearing system useful to dairy industries. Since New Zealand is very strong in dairy industry this system will find a suitable application for pumping milk and other such products in which dirt-free, clean-room atmosphere is required. By providing magnetic bearing it is possible to achieve that and to get rid off the sensors a sensorless scheme has been planned to be implemented in near future.

REFERENCES

[1] J.P.Yonnet, "Passive magnetic bearings with permanent magnets", *IEEE Trans. on Magn.,* vol. 14, no. 5, pp. 803-805, Sep. 1978.

[2] J.Delamare, E.Rulliere and J.P.onnet, "Classification and synthesis of permanent magnet bearing configuration", *IEEE Trans. on Magn.,* vol. 31, no. 6, pp. 4190-4192, Nov. 1995.

[3] S.C.Mukhopadhyay, T.Ohji, M.Iwahara and S.Yamada, "Design, analysis and control of a new repulsive type magnetic bearing", *IEE proc. on Elect. Pwr. Appl.* , vol. 146, no. 1, pp. 33-40, Jan. 1999.

[4] S.C.Mukhopadhyay, T.Ohji, M.Iwahara and S.Yamada, "Modeling and control of a new horizontal shaft hybrid type magnetic bearing", *IEEE Trans. on Ind.. Electronics* Vol. 47, No. 1, pp. 100-108, Feb. 2000.

[5] S.C.Mukhopadhyay, T.Ohji, T.Kuwahara, M.Iwahara, S.Yamada, F.Matsumura, "Comparative studies of levitation and control performances of two types single axis controlled repulsive type magnetic bearing", NASA periodicals, Vol. NASA/CP-1998-207654, pp 393-405, May 1998.

[5] T.Ohji, S.C.Mukhopadhyay, M.Iwahara and S.Yamada, "Performance of repulsive type magnetic bearing system under nonuniform magnetization of permanent magnet", *IEEE Trans. on Magn.,* vol. 36, no. 5, pp. 3696-3698, Sep. 2000.