LOW COST ACTIVE MAGNETIC BEARINGS FOR HARD DISK DRIVE SPINDLE MOTORS

R. Vuillemin,[1] B. Aeschlimann,[1] M. Kuemmerle,[1] J. Zoethout,[1] T. Belfroid,[1] H. Bleuler,[1] A. Cassat,[1] P. Passeraub,[1] S. Hediger,[1] P. A. Besse,[1] A. Argondizza,[2] A. Tonoli,[2] S. Carabelli,[2] G. Genta,[2] G. Heine[3]

Abstract: *This paper presents the design and implementation of a contact free Active Magnetic Bearing (AMB) and a vector controlled permanent magnet synchronous motor-bearing combination in a conventional Hard Disk Drive (HDD). The suspension and drive unit fits into the space formerly occupied by the spindle ball bearings.*
The controller design has to take into account the dynamics of the disks mounted on the rotor which can cause instability of the AMB due to strong gyroscopic effects and vibration of the disks.

Rotational speeds higher than 10.000 rpm have been achieved without stability problems. The total power losses of the first prototype magnetically borne motor are in the same order of magnitude as motors with conventional bearings running at this speed.

1. Introduction

Magnetic hard disk drives are highly optimized low cost and mass produced mechatronic systems. Up to now data storage density on the disks has been doubled every year, thus HDDs continue to outperform competing storage technologies.
One of the most limiting factors to further improvement is the presence of non predictable vibrations (non repetitive runout) of the rotating disks. These are mainly caused by the spindle ball bearings and the misalignment of the stack of disks on the rotor hub which can lead to disk fluttering.

Contact free suspension by AMBs could help to solve some of the major problems caused by spindle ball bearings. AMBs offer many advantages compared to other bearing types. Among these are: absence of mechanical friction and wear, no need of

[1]Institut de Microtechnique, Swiss Federal Institute of Technology (EPFL), 1015 Lausanne, Switzerland.
[2]Dipartimento di Automatica e Informatica, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy.
[3]Seagate Technology Inc., Motor Group, P.O. Box 66360, Scotts Valley, CA 95067, USA.

lubrication and actively controlled precise positioning.
These features make AMBs very suitable for the HDD applications. They can actively damp vibrations occurring in the system. The axis of rotation is not fixed by the alignment of some mechanical parts, as in the conventional case. Instead, the rotor is free to rotate about its mass geometric principal axis. This eases the requirements on balancing.
On the other hand, the low production cost of HDDs will make the realizatioin of magnetically borne HDDs difficult.

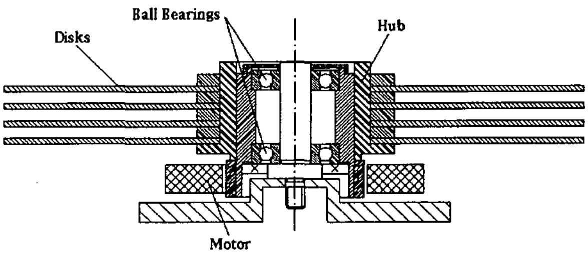

Fig. 1 Cut through a conventional HDD spindle

2. Bearing Configuration

2.1. Overview

The suspension unit consists of an AMB [11] used as the upper bearing and a vector controlled permanent magnet synchronous motor-bearing combination, called bearingless motor, as the lower suspension and drive unit [3, 5, 6]. A passive magnetic bearing based on repulsive permanent magnets can be provided for increasing the stiffness in axial direction.
Inductive gap sensors for the position feedback are placed at the outer side of the hub.

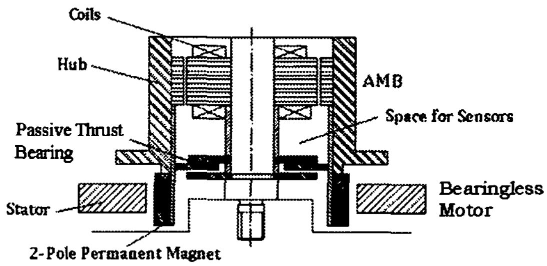

Fig. 2 Cut through the fully suspended HDD spindle

2.2. The Upper Radial Bearing

The AMB is based purely on reluctance forces and consists of four opposed electromagnets. The magnetic actuators of the AMB can compensate accelerations up to 10*g* on the system without touchdown of the rotor. They have been analytically and numerically optimized [9, 10] for power consumption. The results of the optimization were verified with FEM and are shown below (Fig. 3).

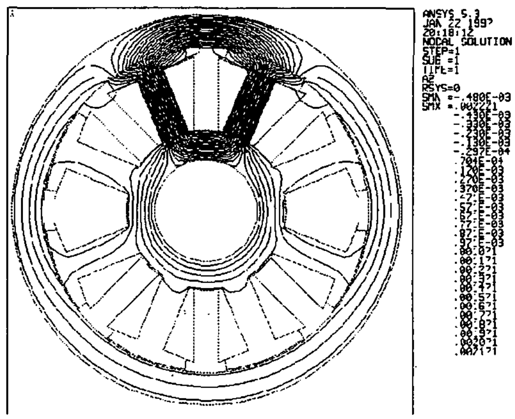

Fig. 3 Maximum forces for prototype AMB: 971 [N/m] = 10.2 [N]

2.3. The Vector Controlled Bearingless Motor

A rotor with one pole pair (p1 = 1) permanent magnet is used for the bearingless motor.
The stator creates torque and radial forces on this permanent magnet simultaneously.
This is made possible by two separated sets of windings on the stator [3, 6]. One set provides the torque with field orientated

control, the other one generates a radial force.

The additional set of windings for the force generation has to be able to create a radial force for the lower radial bearing. This can be done with: $p2 = p1 \pm 1$, $p2 \bullet 1$ pairs of poles. The prototype uses a $p2=2$ pole pair winding on the stator for radial force generation. The 12 pole stator is taken from a conventional HDD (Fig. 4). This configuration is easy to implement but does not represent the optimum configuration for motor and bearing.

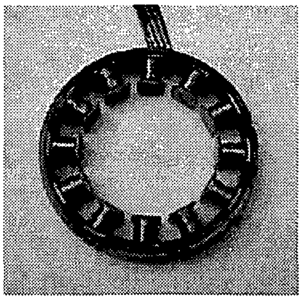

Fig. 4 Conventional 12 pole stator used for motor-bearing. The original 8 pole permanent magnet of the conventional HDD rotor is replaced by a 2 pole radial magnetized permanent magnet.

The original winding scheme (Fig. 5) is replaced by the motor windings (Fig. 6) and the separated bearing windings (Fig. 7).

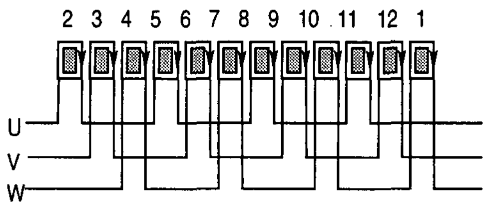

Fig. 5 Conventional coil winding scheme for 8 pole rotor and 12 pole stator.

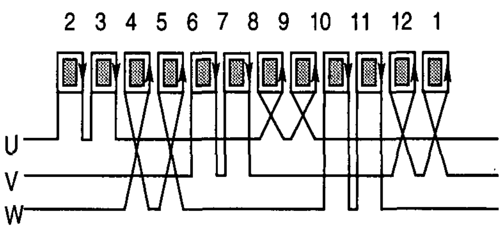

Fig. 6 Scheme for motor coil windings of the bearingless motor with 2 pole permanent magnet.

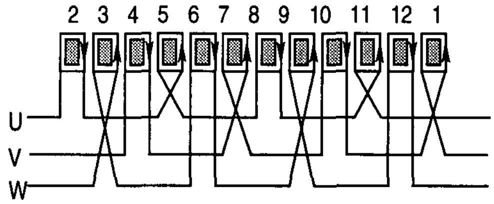

Fig. 7 Scheme for bearing coil of the bearingless motor with 2 pole permanent magnet.

2.4. The Passive Thrust Bearing

The axial displacement of the rotor in the current setup is stabilized by the permanet magnet of the bearingless motor. The stiffness and the damping of this bearing are low. However, an experimental work at the institute showed, that it is possible to use three repulsive permanent magnets as thrust bearing. The magnets have the shape of a ring and are magnetized in thrust direction. One ring is mounted on the rotor, while the other two are attached to the stator (Fig. 2) The damping of the axial movement can be done by means of reluctance forces in the radial bearings [14].

3. Modelling

3.1. Mechanical Model of the Rotor

The given HDD rotor configuration shows strong gyroscopic effects ($J_Z / J_X \approx 1$). According to [12], conservative and stable systems remain stable under influence of gyroscopic effects. AMBs are not conservative. This means that a perfectly stable AMB at standstill can become unstable at higher rotational speeds.

The figures below (Fig. 8, Fig. 9) show the first two structural vibration modes of the flexible disks which can be excited by the controller.

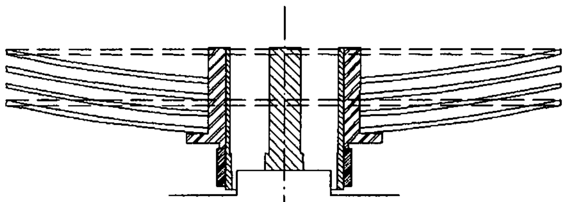

Fig. 8 Axial mode.

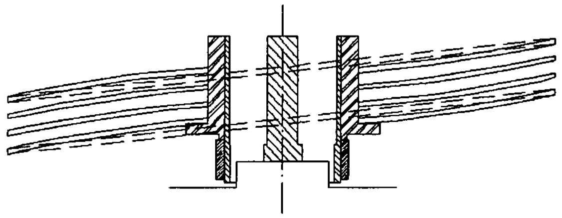

Fig. 9 Radial mode.

The radial and axial bearing stiffness has a direct influence on the frequencies of these modes. Currently, an FE-model of the rotor [2, 7] including the radial AMB actuators is investigated for a refined controller design. The axial bearing remains passive. Its stiffness influences only the axial modes while the radial bearing stiffness only influences the radial modes. This means that the the radial and axial movements are completely uncoupled.

Speed [rad/sec]	[rpm]	(0,0) Mode [Hz] (axial)	(1,0) Mode [Hz] (radial)
0	0	779	644
200	1909	780	677
400	3820	783	712
600	5730	788	750
800	7640	794	789
1000	9549	803	831

Tab. 1 Axial and radial modes

Additionally, the controller has to guarantee a certain robustness at all speeds of rotation. As shown in (Tab. 1), the frequencies of the modes change with the speed of rotation.

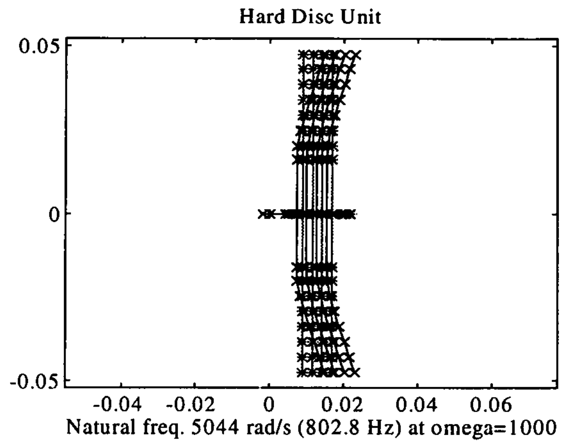

Fig. 10 Axial mode at omega=1000 [rad/sec].

3.2. Model of the Magnetic Actuators

To introduce the magnetic forces onto the rotor model, the AMB has been modelled with the linear force equation:

$$f_x = k_s x + k_i i$$

The two force constants k_s and k_i have been calculated analytically and verified by FEM [8]. The values obtained are given in Tab. 2:

	Analytical calculation	FEM
k_s	1902 [N/m]	2336 [N/m]
k_i	1.33 [N/A]	1.59 [N/A]

Tab.2: Values of ks and ki analytically calculated and verified with FEM.

The bearingless motor has been modelled in [3]. No further calculations concerning the bearingless motor have been made at the moment.

4. Gap Sensors

Gap sensors have to be developed specifically for our application, as commercial sensors are both too big and far too expensive. In a collaboration with the Institute of Microsystems (IMS) at EPFL, we are working on the miniturization and the full integration of a mass producible and low cost inductive type sensor. IMS provides an ASIC with the necessary

electronic interface [13]. The detection principle used is simple and robust.
Two different sensor configurations have been built. The ASICs are mounted on special shaped PCBs. One configuration contains three ASICs and is able to measure three degrees of freedom whereas the other contains two ASICs. By using SMD technology and specially designed, thin PCBs, both configurations fit inside the tight available space.
Fig. 11 shows a photograph of both sensor PCBs. First tests with this sensor are promising. However, they have not been used yet to run the current setup.

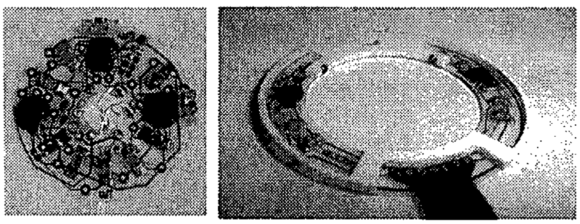

Fig. 11 Left: Sensor PCB with three ASICs and copper coils mounted. The outer diameter of the PCB is 18 mm. Right: Two sensors mounted on a PCB ring reinforced by a ceramic ring. The outer diameter is 35 mm.

5. Control and Experimental Results

A multichannel digital controller is used to control the system. The controllers were designed on Matlab/Simulink™ and compiled to a C40 DSP. A new controller card, based on the TMS320F240 fixed point microcontroller is currently under development. Fig. 12 shows the control system with the used sensors.

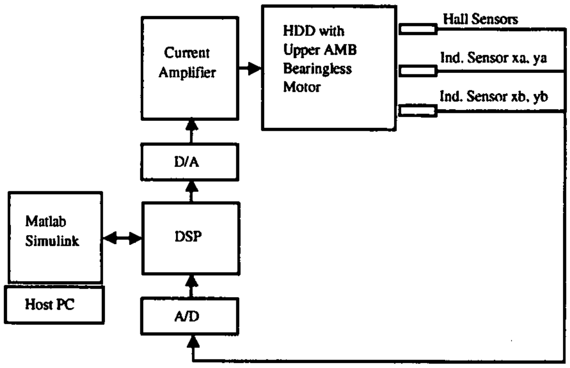

Fig. 12 DSP based controller system and plant.

5.1. Control of AMB

The AMB system is currently controlled by two independent digital PD controllers in radial direction. The control parameters remain constant over all rotational speeds.

Higher order controllers have been designed. In simulation they show better dynamic performance than simple PD controllers. They have not been implemented yet due to the increase of calculation time on the DSP.
The experimental results based on the PD controller show a very robust behavior to variations of the airgap which means that precise positioning of the rotor over a large range is possible. By extending the PD to a PID controller, « infinite » static stiffness (position independent of static load) of the AMB can be produced.

5.2. Control of Bearingless Motor

The angular position detection necessary for the flux transformation is done with hall devices. The coils are driven with analog bi-polar power amplifiers with internal current feedback control.

The position error e (Fig. 13) is compensated by the magnetic bearing controller. The compensation forces have to be transformed into the rotating system. Finally, a Park transformation into the 3 phases of the motor is carried out.

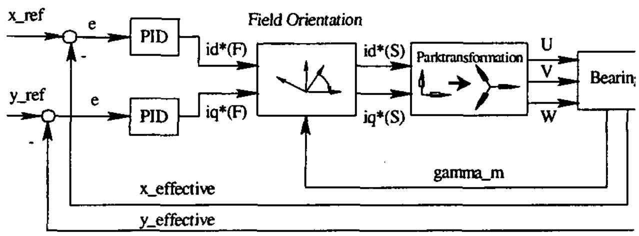

Fig. 13 Control scheme of bearingless motor (bearing part). Conventional motor controllers can be used for the control of the motor.

5.3. Measurements

The following figures show the first measurements which have been taken on the first prototype. The measurement results reported in this paper have been obtained with commercial sensors. Fig. 14 and 15 show results at a speed of rotation of 2000 rpm. The unit of the time axis is [sec], the displacements x and y are given in [m] and the currents in [A].

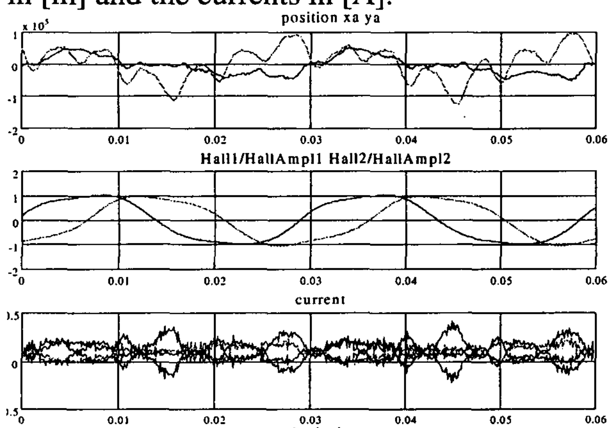

Fig. 14 Measurement in AMB at 2'000 rpm

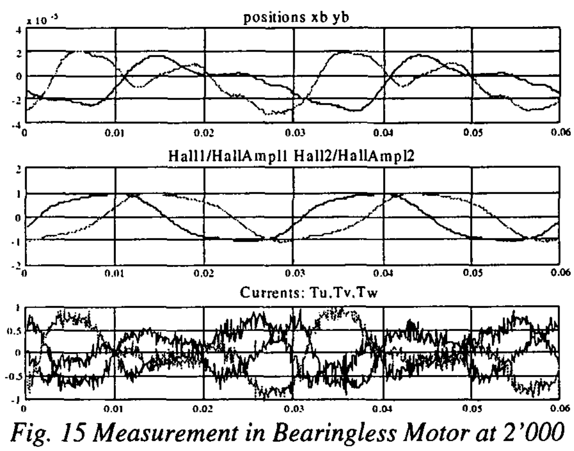

Fig. 15 Measurement in Bearingless Motor at 2'000 rpm

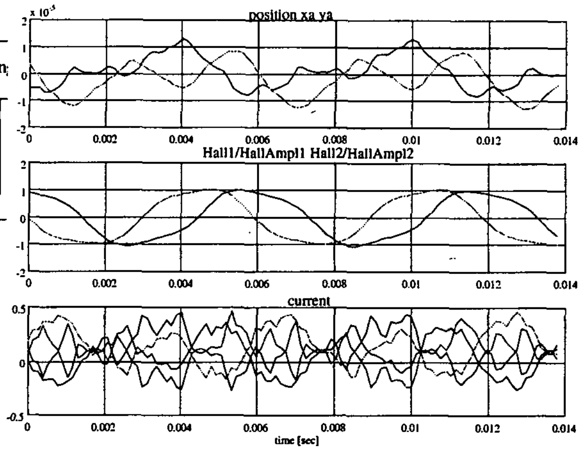

Fig. 16 Measurement in AMB at 10'000 rpm

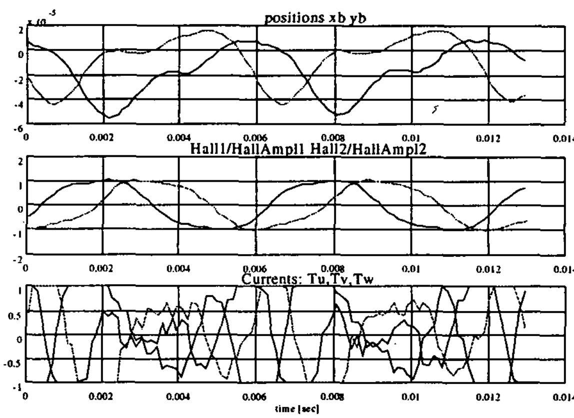

Fig. 17 Measurement in Bearingless Motor at 10'000 rpm

11000 rpm	max. speed tested
10W	peak power consumption (given by controller saturation)
5.75W	power consumption normal operating condition (AMB with motor-bearing)
0.75W	power consumption in AMB
3W	power consumption of motor-bearing (bearing part)
2W	power consumption of motor-bearing (motor part)

Tab. 3 Power consumption of the magnetically borne HDD motor

The experimental performances obtained so far are preliminary leaving ample space for further improvements. In the present setup, the bearingless motor is based on standard components of a commercially available

HDD motor. No optimization at all has been carried out on these components while the magnetic circuit of the upper AMB is closer to an optimum. Nevertheless, the power consumption of the AMB under normal operating conditions can be drastically decreased by a refined controller which enables the rotor to rotate with minimal bearing forces about its mass geometric axis.

6. Conclusions and Outlook

In a fairly straigthforward AMB system design contact free suspension and rotation of a HDD spindle has been achieved. The machining of the mechanical parts has not been very precise. Yet sub-µm positioning precision at standstill and about 4 µm peak to peak repetitive positioning precision during full speed rotation are now being achieved. The system can be operated in all positions relative to gravity.

Our next prototype which is currently under development will have position sensors integrated in the bearings. Other important topics will be the further optimization of the actuators, especially the bearingless motor, and a more refined controller design. This will further reduce the total power consumption of the magnetically borne motor at a nominal speed of 10'000 rpm to below *2 W*.

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