Wide-Gap, Electro-Permanentmagnetic Bearing System with Radial Transmission of Radial and Axial Forces

Karl Boden

Kernforschungsanlage Jülich GmbH, Institut für Grenzflächenforschung und Vakuumphysik, Postfach 19 13, D-5170 Jülich, F.R. Germany

Abstract

The unique features and applications of this magnetic bearing essentially result from two facts: (1) The only bearing components attached to the rotor are non-laminated ferromagnetic steel collars or cylinders; (2) all radial as well as axial forces are transmitted via radial gaps. The stator assembly needs no axially overhanging components that might impose restrictions on the rotor design and axial mobility. Due to the use of flux modulation technique wide radial gaps (25 mm are realised) can be provided at virtually zero-power conditions. The large gaps allow for effective encapsulation and shielding of rotors at elevated (or low) temperatures, corrosive environment, voltage potentials, and pressure. A 2-kg X-ray rotary anode was operated under high-vacuum conditions at + 100 kV anode potential, 600°C temperature at the bearing collars and speed 18,000 r.p.m. with 13 mm radial gaps. The complete X-ray tube is easily exchangeable by removing it from the stator assembly along the axial direction. Similar handling conditions were achieved with hollow cylindrical rotors (up to 500 m/s periphal speed at the bearing gap), spin turbines and choppers (up to 90,000 r.p.m.), and with long-stroke supporting shafts for crystal pulling plants.

Introduction

The magnetic bearing system described is part of development activities, which started in KFA Jülich in 1974 on the basis of previous work and experience of the involved staff. At the beginning most effort was directed to vacuum compatible magnetic bearing configurations but in the meantime various types of magnetic bearings for a wide field of applictions were developed, manufactured and tested, ranging from one-axis to five-axis actively controlled degrees of freedom.

This paper presents a special one-axis passiv stabilizing magnetic bearing, its particularity and some applications.

Magnetic bearings

For rotating equipment, five degrees of freedom of the rigid body have to be constraint, three attached to the translational motion and two degrees of freedom attached to the rotational motion about the cross-axes, i.e. perpendicular to the rotational axis. Only the motion in the rotational axis should not be constraint in order to allow free rotation of the suspended body around this axis and keep the drag torque as small as possible. A lot of different magnetic bearing systems are developed, including actively and passively stabilizing bearings, which fulfil the mentioned conditions. According to Earnshaw's theorem at least one degree of freedom must be actively controlled. Of course, a magnetic bearing with only one active stabilization solves all bearing problems for a few applications and seems to be the best configuration at all. But, taking in consideration simplicity of the rotor design, problems with high speed, damping, elevated temperatures, corrosion environment and assembling aspects the presented axially passive and radially active magnetic bearing type meets all this requirements, so that we prefer this special bearing configuration in many cases [1].

Passive axial bearing

The bearing stator has approximately a square cross section with a central hole for the moving body (Figure 1). It comprises at least one axially magnetized annular permanent magnet, which magnetize the compact mild steel part of the moving body via two radial air gaps, the upper gap and the lower one. The mean part of the permanent magnetic flux passes symmetrically one after another a flux concentrating flat steel plate, the upper air gaps, the mild steel collar on the moving part and the lower air gap.
In this radial air gaps the magnetic flux generates attractive forces between the bearing stator and the moving part in axial and radial directions. This forces only depend on the variation of the magnetostatic energy of the system. The system is autonomous - it doesn't comsume energy.
In the axial direction the force to distance characteristic shows a stable working area. In this area a constant force opposite to the magnetic force (i.e. the weight) stretches this "magnetic spring" to a stable equilibrium point. When the magnetic force of the carrier magnet is so dimensioned, that it can safely carry the weight of the moving body, the permanent magnetic

flux is able to provide a stable passive magnetic suspension of the moving body in axial direction without any consumption of external energy.
Since the carrier magnet holds the moving body stable in axial direction, the radially flowing part of the permanent magnetic flux generates an unbalanced force characteristic in the radial directions. The symmetric annular magnet configuration provides a central equilibrium point, where the opposing permanent forces are compensated. At the lightest deflection the moving body is attracted in this direction by the carrier magnet - the equilibrium is unstable.

Active radial stabilization

To stabilize this unstable equilibrium in the radial direction a stabilizing device is required. This device comprises

- contactless sensors for measuring deviations of the rotor position from the equilibrium point or the desired position and means for producing electrical sensor signals in accordance with the deviation
- electronic control devices for amplifying and phase-displacing this sensor signals to produce output signals
- electromagnetic means for producing substantially radially directed magnetic fields which generate restoring and damping forces to the rotor.

The position sensor

The position sensors are preferably small-sized magnetoresistive plates, which are mounted on the inside of the flux concentrating plate in the upper gap, so that they are cut mainly by a radial component of the permanent magnetic flux of the carrier magnet. The change in field strength as a function of the distance produces a change in resistance and forms the sensor signal. The mentioned flux concentration results in a high sensitivity. When operated in differential mode the nonlinear flux-resistivity function is changed to a linear function in the midrange and a null-position is created in the bearing centre.
This sensor system is rather simple and cheap. Beyond it no additional sensor specific rotor peaces are necessary.

Force coil

The electromagnetic coil system (Figure 2) [2] preferably consists of four segment coils, which are wound on a common laminated ring. (Only two segments are figured in the drawing.) They operate in pairs with diametrically opposite coils developing opposing fluxes. The coils of each pair are connected in series to yield the same radial control current. The flux generated by the control current is forced one after another across a first air gap, through the ferromagnetic bearing collar of the moving body, across the opposite air gap and short circuited by the laminated ring, which forms a parallel path for the control fluxes.
The control fluxes dont have to pass the permanent magnet, so that the permanent magnet does not contribute to the control circuit reluctance. On the other hand, the coil system is arranged immediately next to the permanent magnet, so that the permanent magnetic flux passes the lower gap parallel to the control flux. Thus the control flux modulates the normally symmetric permanent magnetic flux differentially and produces controlable radial forces in two perpendicular directions.

Radial gap

The gap flux density depends among other things on the volume of the permanent magnets. The placement of the magnets in the stator permits relatively large area magnets, so that cheap materials with low magnetic energy density can be used and large gaps can be realized without essential restrictions on high bias flux level, which is advantageous for both the sensor sensitivity and the effectiveness of the electromagnetic control coil system.
The radial unbalance stiffness decreases and the homogenity of the permanent magnetic field increases with increasing gap width.
Large gaps allow the arrangement of housing cylinders consisting of non-magnetic material with high electric resistance like stainless-steel, heat-insulators or glasses for effective encapsulation and shielding of the rotor at elavated temperatures, in corrosive environment, in vacuum or at elevated pressure. As there should be an additional clearence between rotor, stator and housing cylinder, both can easily removed to allow withdrawal, exchange or assambling. This clearances also permit axial movement of the rotor

and/or stator during operation, so that both can be adjusted at several desired axial positions, axially transported without touching one another over long axial distances or oscillated by using additional axial field coils or linear motors.

The biasing effect of the control flux by the permanent magnetic flux besides the conversion of the radial instability into a stable one, has the desirable benefits of

- linearizing the force-versus-current relationship
- multiplying the effectiveness of the control ampere-turns
- zero force at zero current in the passive equilibrium position, which consequently represents the reference axis for the position control loop
- minimizing of electric power consumption
- the realization of large radial gaps between rotor and stator.

Control loop

The need of two control loops per bearing complicates the electronic device somewhat. On the other hand due to the use of flux modulation technique the control electronic is freed from linearization networks for sensor and force signals and high-power consumption.

As described before, the control current is fed-back, so that the output command voltage is proportional to the output current or control force. This feedback makes the effect of the coil inductance negligible.

The bearing stiffness is adjustable within the stable area of the control loop. It usually has a frequency characteristic, which allows reduction of unbalancing forces with increasing speed. The damping of the system can also be adjusted by variation of the phase-shifting network.

Electronic balancing of the radially symmetric unbalance forces enables the virtually zero-power method, which is used for minimizing the power consumption and for compensation of the sensor signal drift. Consequently, the electronic control device is characterized by low energy consumption and simple structure, which can be flexibly adapted to the application requirements.

Rotor collar

As already shown, the radial stabilizing control force generated by the electromagnetic coil system is multiplied by the biasing permanent magnetic field strength. The larger the biasing field, the smaller the required ampere-turns of the control system, i.e., that the magnetic polarization of the ferromagnetic rotor collar is the more homogeneous the higher the biasing field can be arranged. Consequently, the hysteresis- and eddy-current losses in the rotor are diminished. The diminution of these losses lowers the generation of heat and permits the use of compact mild steel collars on rotor even in high-speed rotor application. Compared with rotating permanent magnets, steel collars have the essential advantages of high yield strength, high Curie-temperature and corrosion-resistance. The additional fact that no overhanging bearing parts between rotor and stator are needed permits substantial freedom in the rotor design.

Complete bearing system

For the entire suspension of the moving body a second coaxial bearing is needed in order to constraint all radial degrees of freedom (Figure 3). This second bearing can be of identical construction as the one described above [3]. The passive forces in axial direction can be directed to support the first bearing in order to enlarge the axial load capacity in vertical-axis applications. In horizontal-axis applications (Figure 4) the bearings should be arranged to counteract in axial direction, so that one bearing preloades the other one in order to produce a stable equilibrium in the absence of external axial holding forces.

There are a lot of variations and combinations of the magnetic configuration developed [1,2,3,4,5] for example, the arrangement of

- pole-shoes in order to optimize the permanent magnetic flux loop
- additional magnetic force coils in order to influence the axial exerted permanent magnetic force or to stabilize or to vary the axial position
- the bearing stator inside a hollow cylindrical rotor
- multiple gaps in order to enlarge the load capacity and/or the stiffness
- radial magnetization of the permanent magnets
- permanent magnetic material with high energy product.

Rotor drive

For the rotor drive normally a cylindrical rotating field stator is used, which is mounted on the stator. The structure of the rotor armature depends on the motor system. Synchronous and asynchronous drive motors are compatible with the magnetic bearing system. As described above the drag torque is rather low, so that in the absence of external torque very low drive power is required.

Examples of Application

Figure 5	Rotating hollow cylinder (1969)	
	Rotor speed	60,000 rpm
	Velocity in the bearing gap	500 m/s

The cylinder material is high yield strength steel and allows high rotational frequency. The tangential velocity is essentially limited by the yield strength. Due to the absence of axially overhanging rotor and stator parts the rotor is easily dismountable by moving it along the axial direction. This leading feature is used at most of the following applications.

Figure 6	Spinning turbine (1973)	
	Working speed	48,000 rpm
	Fast speed	90,000 rpm
Figure 4	Molecular chopper (1974) [9]	
	Rotor speed	24,000 rpm
	Vacuum environment	
Figure 3	Neutron chopper (1975) [9]	
	Rotor speed	36,000 rpm
Figure 7	Fast light chopper (1983)	
	Rotor speed	84,000 rpm
Figure 8	X-Ray-tube with rotating anode (1979) [6]	
	Rotating frequency	18,000 rpm
	Radial gap	13 mm
	Rotor temperature at bearing parts	$< 600^{o}C$
	Anode potential	> 100 kV

This arrangement has the function of a current switch. The rotor can be moved to two different axial positions by means of an additional axial field coil arrangement. [4].

Figure 9 High speed UHV-Chopper (1986)
Installed at Philips Eindhoven
Corrosive environment
Rotor speed 24,000 rpm

Figure 10 Neutron beam chopper (1986)
Installed at Rutherford Appleton Lab., UK
Rotor speed 36,000 rpm

Figure 11 Apparatus for pulling crystals from the melt (1986) [7,8]. Both, crystal and crucible are carried and transported by magnetically suspended shafts. Since these parts move in clean vacuum or pressure environment inside the housing the stators are arranged outside the housing, and can be axially moved by means of a linear drive. Even with comparatively thick-walled vessels, the gap width (24 mm) is sufficient for accommodation of additional tempering elements, i.e. elements for controlling the temperatures of the housing wall up to 700°C, and for cooling the stator unit. Consequently this machine permits for the first time to make use of the "hot-wall"-method for the growth of monocrystals from so called III-V compounds, especially GaAs and InP at an industrial scale. In a test setup several crystals of semiconductor material with a weight up to several kilogramms have been pulled.

Conclusion

A practical non-contacting magnetic bearing system using flux modulation techniques has been developed. It has been worked very effectively, yet the bearing parts are very simple and inexpensive. For example, flat annular speaker magnets, made of cheap Bariumferrite-material, simple coils and sensor systems and mild steel collars make up the entire parts of stator and rotor.

The bearing configuration permits

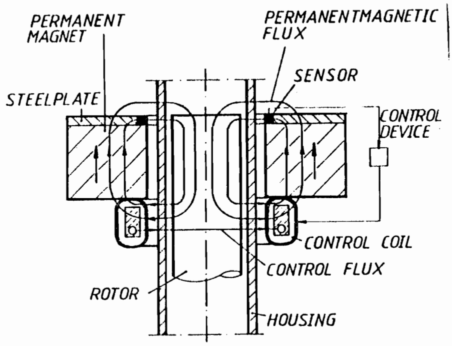
- wide radial gaps
- very simple rotor structure, far-reaching freedom in rotor design
- no axially overhanging bearing components of rotor and stator unit
- high rotor speed
- low and high rotor temperature
- clean and corrosive atmosphere
- vacuum and pressure environment

- axial mobility and position control of rotor and stator during rotation
- easy installation
- low power consumption

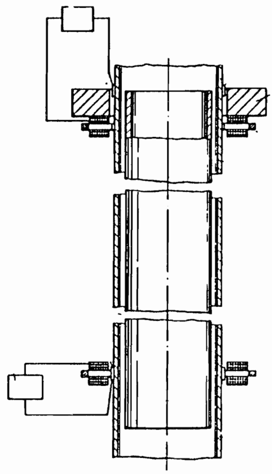
The bearing concept thus covers a lot of complex requirements and sets up new fields of design and application.

References

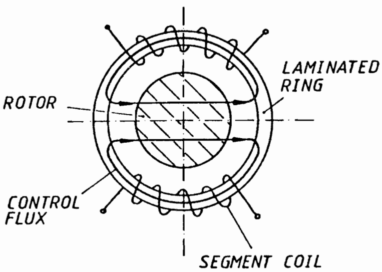
1. German patent 1750602, 1933031, 1967085, 1967086
2. " " 2213465
3. " " 2312001
4. " " 2420814
5. " " 2420825
6. " " 2716079
7. " " 3432467
8. " " 3530417
9. R. Hackenberg, W. Ebert, "High precision particle beam chopper" paper presented at First Int. Symp. on Magnetic Bearings, June 6-8, 1988


PERMANENT MAGNET
PERMANENTMAGNETIC FLUX
SENSOR
STEELPLATE
CONTROL DEVICE
CONTROL COIL
CONTROL FLUX
ROTOR
HOUSING

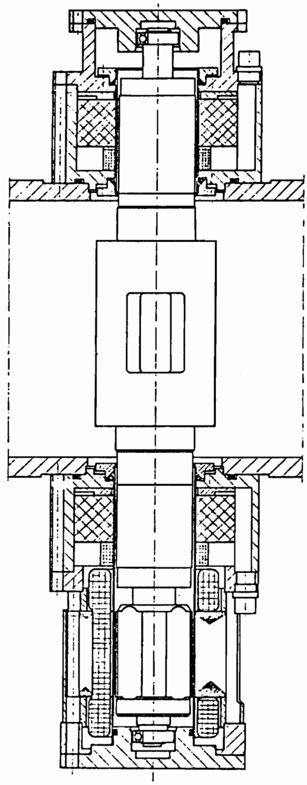
1



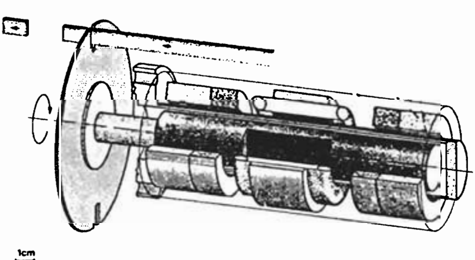
5


LAMINATED RING
ROTOR
CONTROL FLUX
SEGMENT COIL

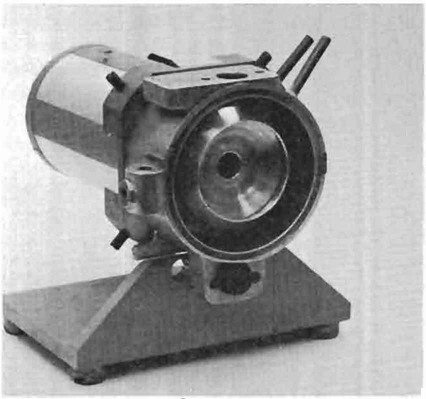
2



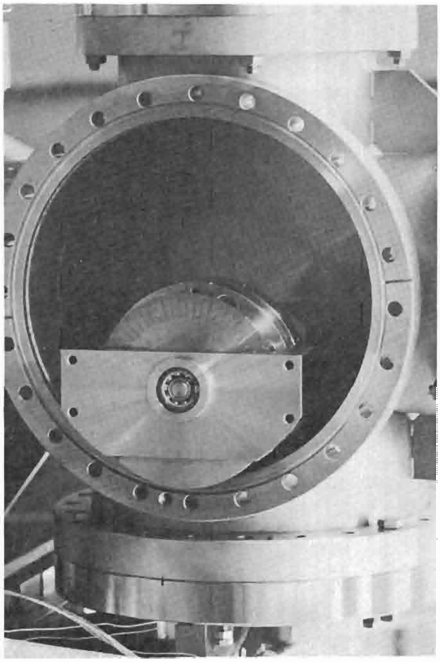
3


1cm

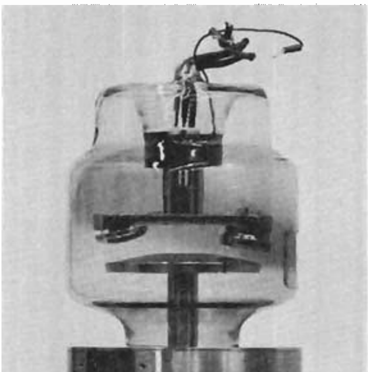
4



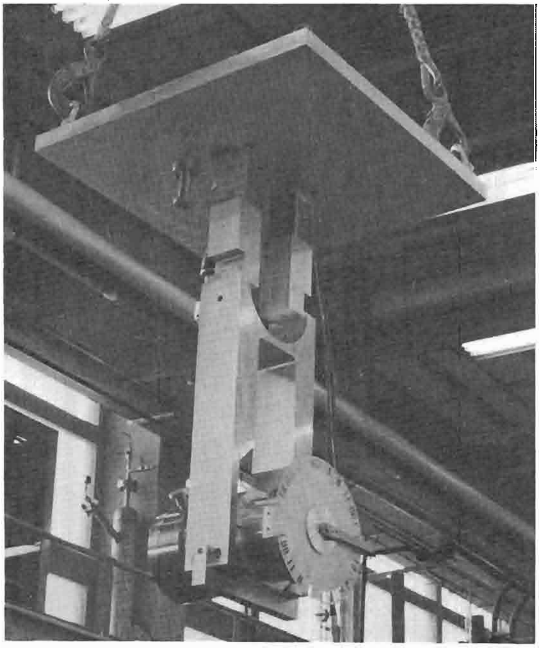
6



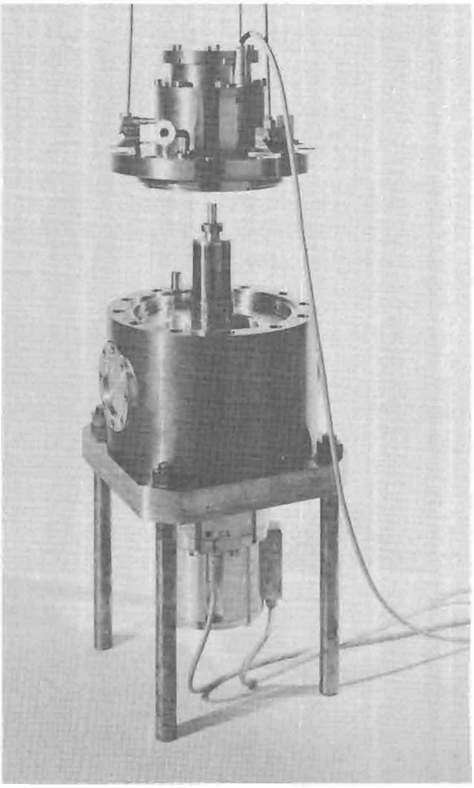
7



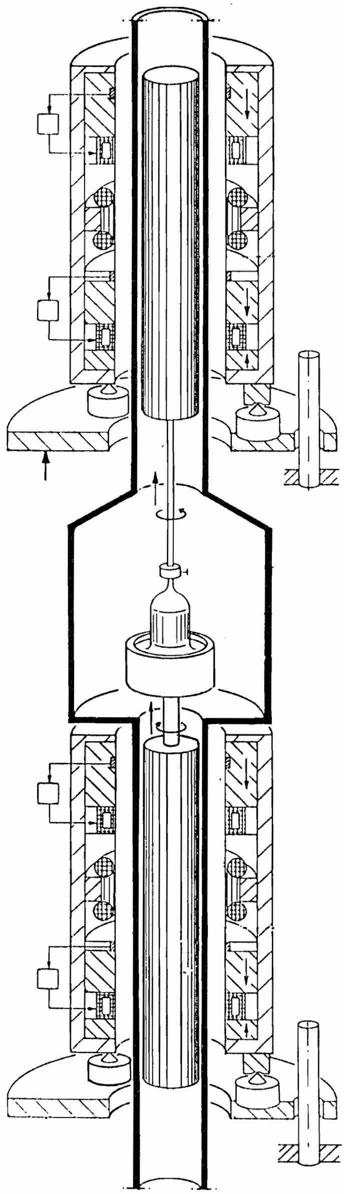
8



9



10



11