M-BEAM (MAGNETIC BEARING FOR BRUSHLESS DIRECT CURRENT MOTOR IN MICROGRAVITIY)

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1. ABSTRACT

The M-BEAM (**m**agnetic **bea**ring for brushless direct current **m**otor in microgravity) project is an experiment about the design and construction of a fully wear and maintenance free brushless DC motor for microgravity. The objective is achieved by a magnetic bearing system stabilizing the rotor. This motor will work free of contact between rotor and stator due to magnetic bearings avoiding any friction on components. The results of the M-BEAM project will show the possibility to replace conventional lubricated bearings, such as they are currently used in space applications of reaction wheels, through these new and innovative magnetic bearings. This has many advantages for the space technology as it would significantly improve the bearing systems of reaction wheels, which leads to an increased life span of satellites and expensive services could get avoided. The space program REXUS provided by ESA, DLR and SNSB offers the M-BEAM experiment the unique opportunity to test it on a sounding rocket under real microgravity conditions.

1.1 REXUS Space Program

M-BEAM is part of the REXUS space program (Rocket Experiments for University Students) of the European Space Agency (ESA), the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB).

Figure 1. REXUS Logo

The idea of the M-BEAM experiment has convinced against many project proposals from universities all over Europe and was selected to be launched on a REXUS sounding rocket in February 2011. M-BEAM flies on a ballistic flight to an altitude of 85 km and can be tested under actual space conditions.

More detailed information is given at www.rexusbexus.net.

2. TECHNICAL OVERVIEW

The brushless DC motor sets the rotor in motion. The magnetic bearing system stabilizes the rotor by producing magnetic forces. The regulation unit continually receives position data of the rotor by the sensor unit and transforms it into control currents for the active magnetic bearings. This makes actuating magnets of the magnetic bearing system produce a magnetic force which keeps the rotor in nominal position. The measured position data gets stored in the storage unit.

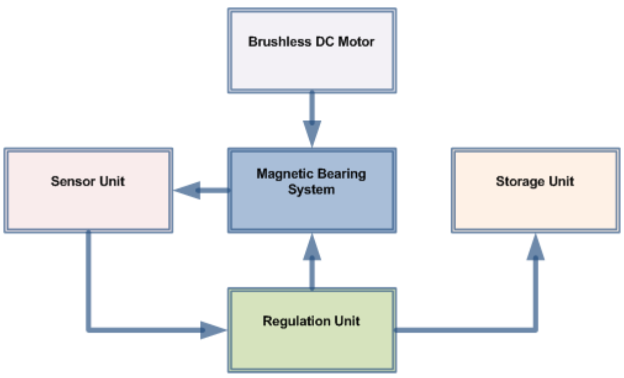

Figure 2. Technical Overview

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2.1 Mechanical Design

The M-BEAM project is designed to fit into the rocket cylinder of REXUS sounding rocket. Its overall height is 238 mm and weights 3.43 kg.

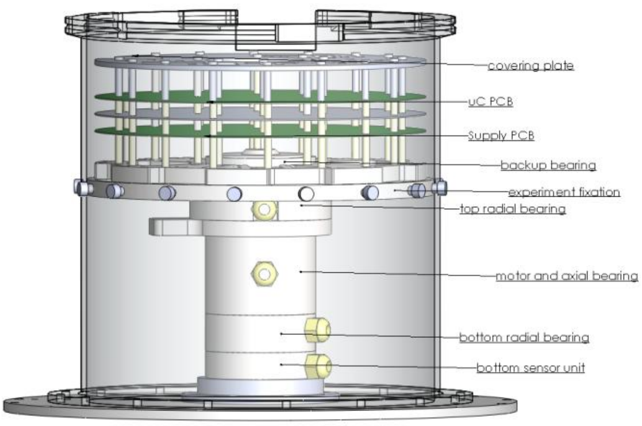

Figure 3. Mechanical asembling

2.1.1 Motor

A commercial brushless DC motor is used from the company "Plettenberg Motoren". The motor is fixed to its module by just deploying it into the module. The axial bearing stator is holding the motor additionally. When the motor is operating it can reach rotational speeds up to 40.000 rpm.

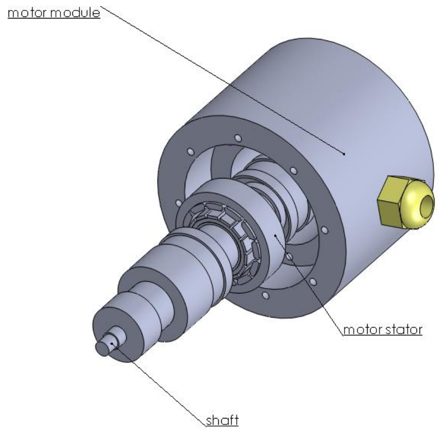

Figure 4. BLDC motor

2.1.2 Backup Bearings

Backup bearings are in use in case of regulation failure or power breakdown. Two ball bearings with a bigger outer diameter than the shaft diameter are fixed onto the top and bottom plate of the experiment module.

3. ACTIVE MAGNETIC BEARING DESIGN

The active magnetic bearing (AMB) is responsible to limit the shaft to four degrees of freedom (x, y, yaw, pitch). This means it has to keep the shaft of the motor in the radial epicenter of the whole construction.

3.1 Principle

The measured data, collected by the displacement sensors and processed by the microcontroller cause a signal which controls the behavior of the active magnetic bearing. Depending on the position of the shaft, the current through and consequentially the force of each of the four electromagnets is varied in order to keep the shaft in the centre of the bearing.

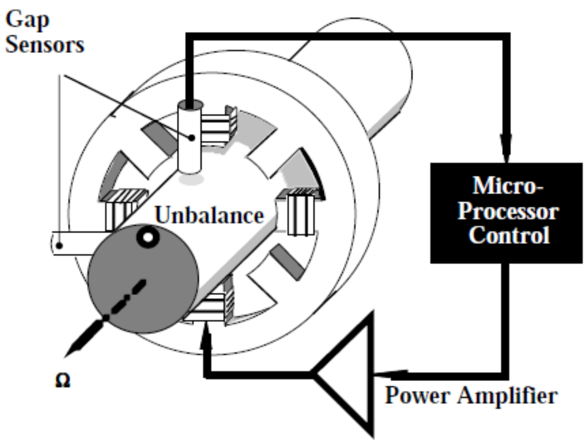

Figure 5. AMB principle

3.2 AMB Components

Stator

The realization of the radial bearing-concept is achieved by the use of the stators of stepper motors (Nanotec ST4118S1401). These motors are really appropriate for this application because they already have the right geometry and they are manufactured and tested very well. Always two of the eight stator-coils are interconnected in a way that one of the two coils represents the north and one the south pole and the magnetic field is short-circuited over the stator sheets.

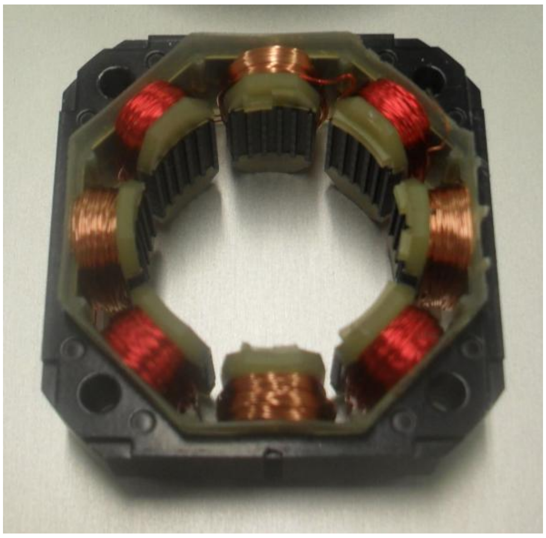

Figure 6. AMB stator

Rotor

The rotor ring is made of a chrome-steel with excellent magnetic properties to maximize the force of the AMB. It is manufactured highly precisely and ensures a small air gap of 0.3 mm (0.15 mm on each side). This rotor is glued with the shaft.

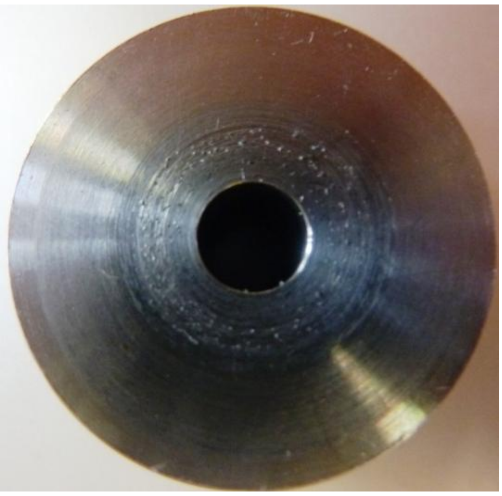

Figure 7. AMB rotor

Radial Bearing – PCB

The PCB of the radial bearing is mounted as close as possible. This small PCB is designed to connect the coils of the stator in the way shown above and to connect the radial bearing with the main PCB.

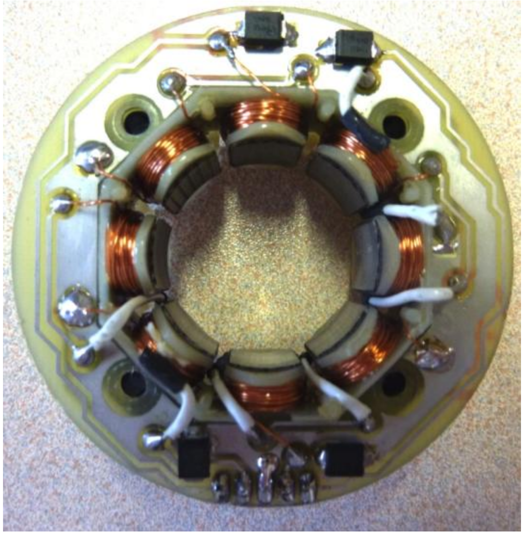

Figure 8. AMB with PCB

3.3 AMB Parameters

Table 1. AMB parameters

Parameter	Value
Number of poles	8
Number of turns per pole	80
Connection of coils in winding is	Series
Diameter of wire	0.25 mm
Resistance of winding(one coil)	1 Ω
Rated current	2 A
Maximum force at maximum air gap	9 N
Outer length of stator	40.2 mm
Air gap diameter	27.2 mm
Pole height	12.7 mm
Pole thickness	9 mm
Rated air gap length(on each side)	0.15 mm

3.4 Current feed of the Electromagnets

There are different ways to drive magnetic bearings, in this project a differential control of the electromagnets was selected:

Two opposing active electromagnets, which are positioning the rotor according to a predetermined position set point, form one pair of magnets. The coils are driven by a constant load current i_0 (it works against gravity and is not applicable in the weightless space) and a variable control current i_x (for shaft positioning). While one magnet gets powered by the current $i_0 + i_x$ the opposite one gets driven by the current $i_0 - i_x$ (differential control). The control current is specified as a control signal from the digital controller. The control signal can is provided as a digital pulse width modulation (PWM) signal.

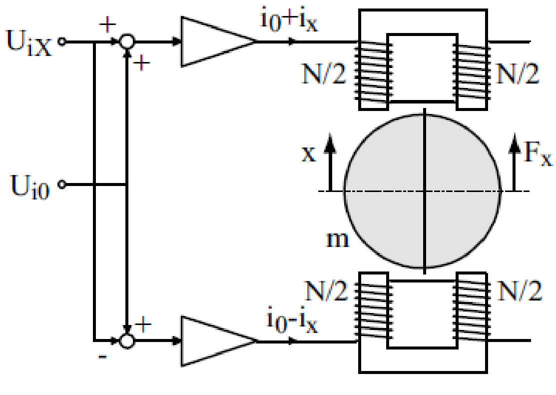

Figure 9. Differential control of an AMB

The digital controller calculates the difference between a predetermined position = set point and the actual position value. Out of this control deviation the control signal is calculated by a PD control algorithm.

From the difference circuit between two bias circuits two advantages are provided:

1. linearization of the force-current curve (Fig. 10).
2. slope of the force-current curve (determined $_I k$ and $_s k$) is adjustable

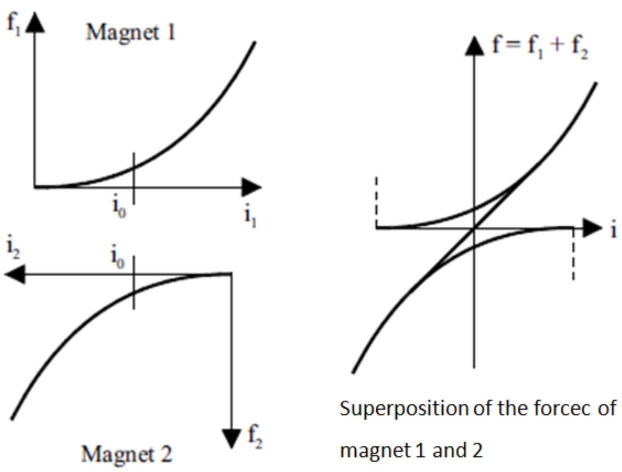

Figure 10. Linearization of the characteristic force-current curve

3.5 AMB Stability Criterion

By the differential control of the electromagnets, a linearized force-current curve (Fig. 10) is obtained. Nevertheless the uncontrolled magnetic bearing is due to the negative slope in the force - displacement curve function an unstable system. At a constant current, the magnetic force behaves inversely proportional to the square of the displacement $f = 1 / x^2$ (Fig. 11).

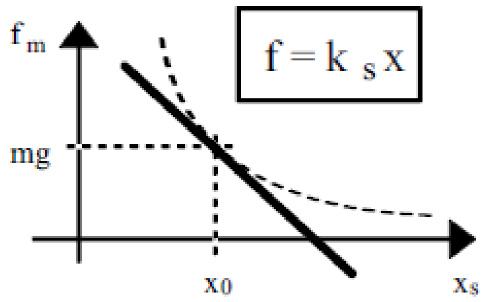

Figure 11. force - displacement characteristic curve of a magnetic bearing (x = x0 – xs)

Therefore the aim is to get a force - displacement characteristic curve with a postive slope like a spring (Fig. 12).

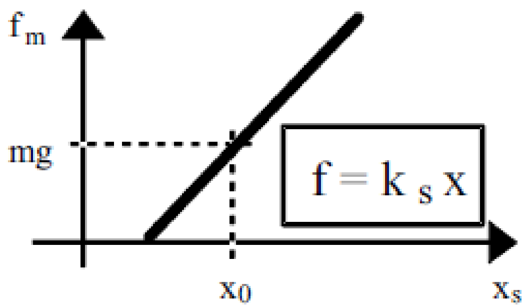

Figure 12. force - displacement characteristic curve of a spring (x = x0 -xs)

3.6 P² – Controller

To reach a linearization of the force - displacement characteristic curve in the magnetic bearing and thus maintain a stable system like of a spring, a P controller with a quadratic characteristic line was implemented in the digital controller. Thus the P ² controller (error = x^2) balances the inversely proportional magnetic force $f = 1 / x^2$ and linearizes the force displacement curve as in a spring. Consequently a stable system can be achieved.

3.6.1 P² Controller Characteristic Line

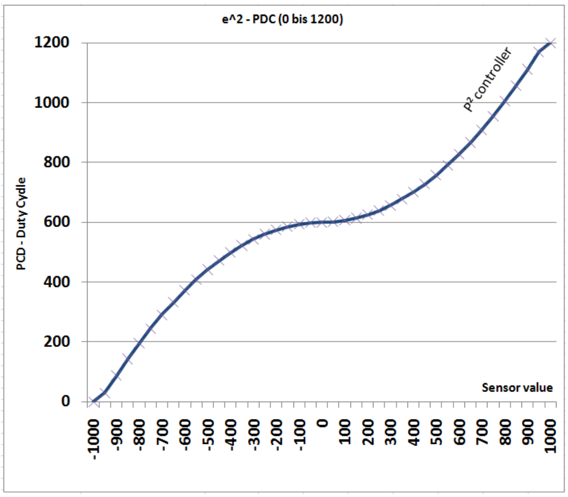

Figure 13. characteristic line of a P² controller

The y axis is showing the duty cycle and set with the register PDC of the microcontroller. It varies between 0 and 1200. Therefore the value 600 means that both magnets (magnet, and complementary magnet) gets driven with the same PWM signal - 50% duty cycle each.

The x axis is showing the sensor value in dependency to the duty cycle of the PWM signal of the magnetic bearings. Its value has a range from -1000 to +1000 and gives back the displacement of the shaft in respect to the zero point. The maximum displacement sensor value of +/- 1000 corresponds to 150 µm shaft displacement from the zero point. The curve shows that the controller responds with increased displacement with an much more increased magnetic force, in this case quadratic. The higher the displacement the stronger the restoring force.

3.7 D - Controller

To obtain an improved control response also a D controller was implemented. The differential term provides the necessary stability of the shaft. In the case of an external disturbance or proposed position change, it has a great damping effect.

4. PASSIVE MAGNETIC BEARING DESIGN

The purpose of the axial bearing is the stabilization lengthwise the shaft up to the maximum stress at 20 g. The estimated load at this acceleration equals about 2 kg (when mass of the shaft equals 100 g). I consists of two repulsing magnets which are mounted on the housing and keeps the shaft centered in axial direction.

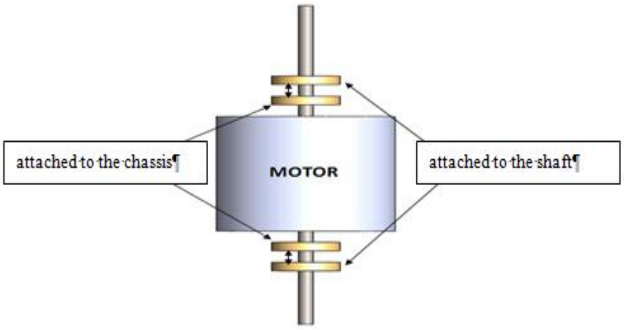

Figure 14. PMB sketch

4.1 Ring-Magnets

Because of the high magnetic flux density and small mechanical tolerances this neodymium-magnets are chosen.

Table 2. PMB parameters

Parameter	Value with unit
Outer diameter	24.5 mm
Inner diameter	18.5 mm
Height	3 mm
Material	35 SH
Surface	gilded
Flux density inside the magnet	1.17 Tesla
Mass	4.54 g

5. Sensor Unit

The sensor unit fulfills following tasks:

- Measurement of the radial displacement in X and Y direction
- Measurement of the axial displacement in Z direction
- Measurement of the rotational speed of the shaft

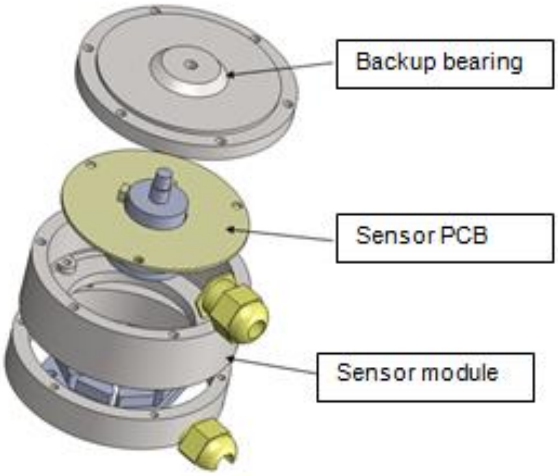

Figure 15. Sensor unit ketch

The sensor unit measures data from a total of 5 displacement sensors. The lower sensor module contains two optical sensors for determining the radial shaft position. The upper sensor module includes 3 optical sensors for determining the radial and the axial shat position.

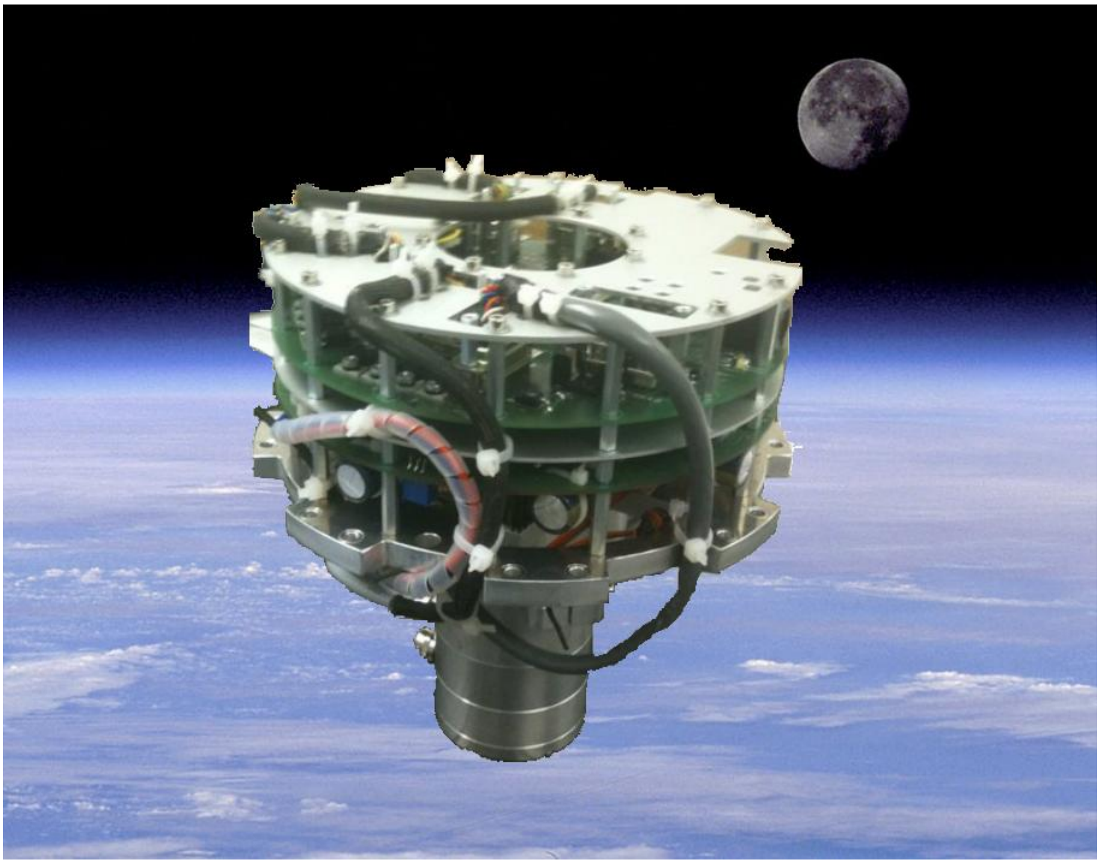

Figure 16. the M-BEAM flight model

6. REFERENCES

1. Precise Digital Control of Active Magnetic Bearings: A Hand Book of Modelling, Control and Disturbance Cancellation in Rotors Levitated Using Active Magnetic Bearings, Sanath Alahakoon: VDM Verlag 2009

2. Magnetic Bearings: Theory, Design, and Application to Rotating Machinery, Gerhard Schweitzer: Springer 2009