THE CHALLENGES OF MINIATURISATION FOR A MAGNETIC BEARING WHEEL

Michael Scharfe*, Thomas Roschke*, Enrico Bindl*, Daniel Blonski*, René Seiler**

(*) Dresden University of Technology, Institute of Precision Engineering
D-01062 Dresden, Germany
Phone: +49 - (0)351 - 463 2247
Fax: +49 - (0)351 - 463 7183
E-mail: Michael.Scharfe@mailbox.tu-dresden.de

(**) ESA/ESTEC, Mechanical Systems Division
P.O. Box 299, NL-2200 AG Noordwijk, The Netherlands
Phone: +31 - (0)71 - 565 5551
Fax: +31 - (0)71 - 565 5637
E-mail: Rene.Seiler@esa.int

ABSTRACT

Reaction and momentum wheels have become standard equipment for three-axis attitude control of conventional satellite classes like those used for telecommunication and remote sensing missions. Owing to very compact mechanical designs and highly integrated electronics, wheels are now also more and more interesting for small satellites in the mass range up to about 200 kg with increasingly demanding requirements on attitude control. In this context, the development of a miniature wheel with a magnetic bearing is discussed.

The paper focuses on the magnetic bearing design process, using magnetic field CAE tools, and on the overall wheel design. A prototype of a compact magnetic bearing wheel, currently under construction, is presented. Moreover, control aspects of the magnetic bearing and the drive motor design are described, and an outlook on potential further improvements and future development steps is given.

1. INTRODUCTION

Today, satellites in geostationary orbits as well as those for LEO missions mostly use ball bearing wheels for attitude control. The technology is considered mature and well-proven and has not changed substantially over the last 20 years. Nevertheless, magnetic suspension for momentum and reaction wheels is pursued in parallel as it can be a promising technical alternative to ball bearings with a number of very attractive features.

Magnetic bearings can offer distinct advantages like virtually zero wear and extremely low friction losses. They do not suffer from stiction-friction and related lubrication effects common with mechanical ball bearings, making them ideal candidates for deep space missions with long lifetime requirements, sometimes long hibernation periods, and wide operational temperature ranges. Earth observation and science missions can furthermore benefit from their potential to have very low micro-vibration and body noise emission levels.

Magnetic bearing wheels of rather large size have been previously developed as e.g. described in [1] and [2]. Such wheels have been used in space already, e.g. onboard the SPOT family satellites by CNES and the ERS satellites by ESA. In this conjunction, the on-ground and in-orbit micro-vibration characteristics of the SPOT4 wheels are discussed in [3]. Furthermore, in [4] the development of a gimballed momentum wheel with five actively controlled degrees of freedom is outlined. By this approach, all three axis of a satellite could be controlled with a single wheel for certain missions.

However, so far the application of magnetic bearing wheels was almost exclusively limited to high-end missions with very demanding requirements, big platforms and the funding conditions, which are compatible with the spacecraft equipment necessary for such missions. For the domain of small satellites, affordable miniature magnetic bearing wheels have not been available in the past.

During the last decade, a general transition in the types of payloads being flown on small satellites can be identified. Mission objectives changed from pure communication and science with low pointing requirements towards earth observation and instruments with three-axis high-accuracy pointing requirements. Still, as most of those satellites are built in environments like universities and small research establishments, reaction and momentum wheels are major hardware cost elements. Therefore, the consideration of magnetic bearings in this context might be even more challenging than for bigger satellites. However, nowadays the associated design, manufacturing and test efforts can be considerably reduced by utilising powerful software tools and state-of-the-art technologies. Therefore, magnetic bearings have the potential to become competitive with respect to ball bearings in terms of performance vs. cost even for low-budget missions.

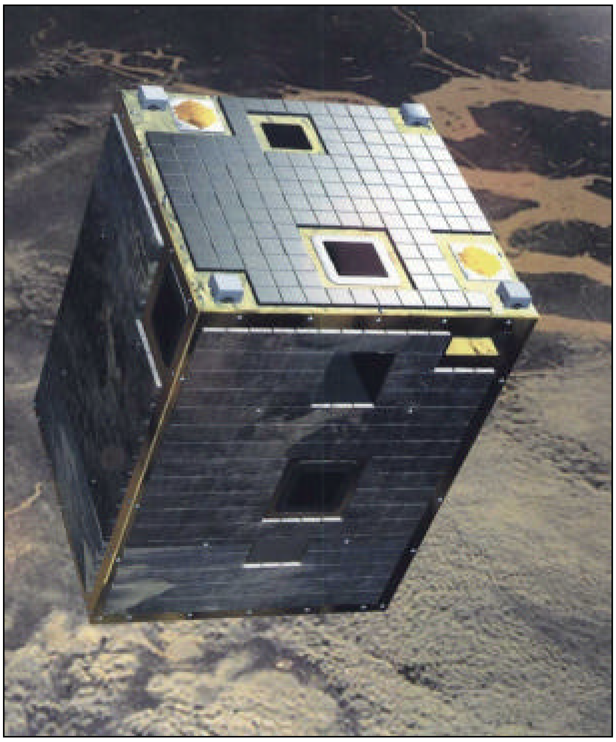

Figure 1: PROBA Satellite (Courtesy of ESA)

A typical example for the target satellite class for a miniature wheel can be found with the PROBA (PRoject for On-Board Autonomy) satellite presently under development by ESA [5]. PROBA features three-axis attitude control in order to satisfy the pointing requirements of the main payload, a Compact High Resolution Imaging Spectrometer (CHRIS). An artist's impression of PROBA is given in Figure 1. As actuators, four ball bearing wheels are used in combination with magneto-torquers for wheel off-loading [6]. Apart from the PROBA wheels, various other types with ball bearings have been recently developed by different entities (see e.g. [7]), and some of them have been successfully flown already.

Recently, a first attempt has been made to apply magnetic bearing wheels also for small satellite projects. In close collaboration with AMSAT, the international amateur radio satellite corporation, magnetic bearing wheels with 15 Nms momentum storage capacity and a mass in the order of 10 kg (including electronics) have been built [8]. They are presently flying on the AMSAT OSCAR 40 (Phase 3-D) satellite, which has a launch mass of approximately 500 kg. Unfortunately, at the time of writing this paper, the wheels were not yet operational in flight.

The present design and development activity has been using the AMSAT wheel design as a starting point. In general, the objectives are to achieve a more compact and robust design, and to optimise the magnetic bearing, the drive electronics as well as the overall mechanical configuration.

2. REQUIREMENTS FOR SMALL SATELLITES

At the beginning of the present wheel development, an extensive survey on small satellite missions has been performed. Key data on more than 250 different satellites have been compiled. Specifically targeting at small 3-axis stabilised platforms, a set of reference satellite & mission data has been established (Table 1).

Table 1: Reference Satellite/Mission Data

Feature	Sat./Mission Specification
Launch mass	100 kg
Power	80 W
Mission type	Earth remote sensing
Main payload	High-resolution camera
Sensors	1 Sun sensor 1 Star sensor 4 Rate sensors
Actuators	4 Reaction/moment. wheels, 3 Magneto-torquers
Max. slew rate	0.5°/s
Pointing accuracy	± 0.2°
Max. allowable jitter	0.001° in 100 ms

Based on the platform performance as well as on the experience with the AMSAT wheels, and utilising a simplified wheel and satellite dynamics model, the following main requirements have been derived for the prototype wheel envisaged:

Table 2: Wheel Main Requirements

Feature	Wheel Target Performance
Angular momentum	0.2 … 0.4 Nms
Speed range	± 5000 rpm
Reaction torque	± 10 mNm
Operation modes	Torque & Speed loop
Operating voltage	28 V DC
Power consumption	2.5 W steady-state @ 1000 rpm 4 W steady-state @ max. speed 20 W peak power
Weight	≤ 2 kg
Main dimensions	Max. diameter 12 cm Max. height 10 cm
Temperature range	- 30 °C … + 50 °C

3. MAGNETIC BEARING CONCEPT

A completely passive and contactless magneto-static bearing, stable in all six degrees of freedom (DOF), cannot be realised under normal conditions. In practice, at least one axis has to be controlled actively by means of electromagnets. Earlier publications on magnetic bearing wheels suggest to control either one, two or five DOF actively [9].

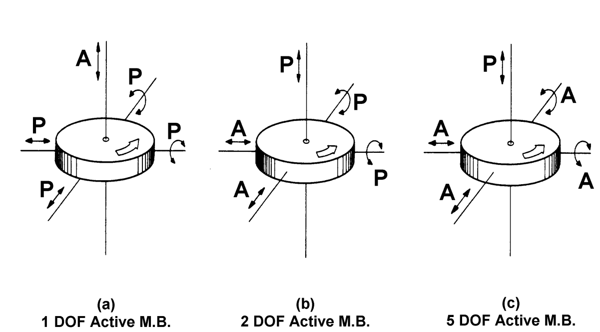

Figure 2: Basic Magnetic Bearing Principles

Different advantages and disadvantages of the individual bearing principles are summarised in Table 3.

Magnetic bearings can be realised by using attractive or repulsive forces. A better mass vs. stiffness ratio can be achieved by using the attractive force mode. Preference was given to the two DOF option where the wheel is actively controlled along two orthogonal radial directions while axial movements and all other degrees of rotor freedom are passively controlled by means of permanent magnets, except for the rotor spin. The two radial axes are controlled by independent control loops. This design principle generally results in a flatter geometry, using less volume and being suitable for panel mounting. Moreover, the two DOF actively controlled bearing allows a high momentum-to-mass ratio of the wheel because some parts of the bearing contribute to the momentum storage capacity. For position detection, four field displacement type inductive sensors are mounted with 90 degrees angular spacing around the flywheel, facing the outside rim surface.

Table 3: Main Properties of the Different Principles

No. of Actively Controlled DOF	Magnetic Bearing Properties
1 (axial)	Simple electronics; relatively low power consumption, but large axial dimensions; rather awkward mechanical construction; passive damping of radial oscillations difficult
2 (both radial)	High radial stiffness due to active control; simple construction; low axial height
5	Complex system, therefore potentially less reliable than other options; offers vernier gimballing capability; special precautions required for testing in 1g

In the wheel design, both permanent magnets and electromagnetic coils are used. Most of the DOF are passively controlled - this offers higher reliability and lower power consumption because the amount of electronics is reduced. The permanent magnets produce the main part of the magnetic flux in the magnetic circuit and the electromagnetic coils modulate this static bias flux, allowing the control of restoring forces on the wheel to keep it centred. This modulation is necessary to provide active control in radial direction under the presence of residual imbalance or external forces.

Another advantage for the active control is the linearised characteristic of force vs. current through the superposition of two reluctance forces in opposite directions. These forces are generated in the air gaps as shown in Figure 3, on the left and right hand side. Rare earth permanent magnets (NdFeB) were chosen because they offer a high energy density and the resulting advantages in terms of mass and volume.

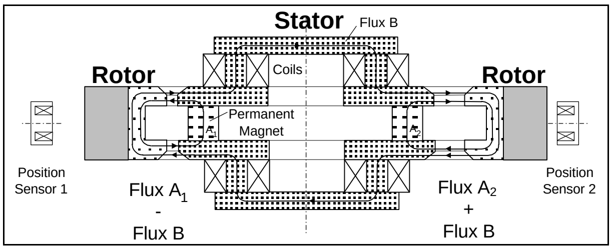

Figure 3: Magnetic Bearing Concept

Figure 3 provides a cross-sectional view of the magnetic bearing. A bias flux is generated across the air gap, shown in paths A_1 and A_2, supporting the weight of the flywheel in the axial direction. If the wheel is not centred, the permanent magnets will create a destabilising force, which pulls the wheel even further away from the centre. The control system will detect this motion through position sensors at the wheel's outer diameter and generate a corrective flux B by sending current through the stator coils. In the air gap, this control flux B subtracts and adds to the static fluxes A_1 and A_2 generated by the permanent magnets. By subtracting flux at the narrow gap side (left) and adding flux at the wide gap side (right), the magnetic bearing produces a net restoring force to centre the flywheel.

It is important to note that the two axis active working principle governs the overall wheel design in terms of the arrangement of the motor assembly as well as the mechanical configuration and main dimensions.

4. MAGNETIC BEARING DESIGN

One of the main design goals for the compact magnetic bearing wheel is to achieve a high moment of inertia and, hence, a high momentum capacity at low mass.

Therefore, the rotor mass shall be concentrated towards the outer rim. Consequently, heavy parts like the motor magnets and the motor return ring have to be placed there. The actual magnetic bearing is located in the centre of the wheel and was designed first. At a later stage, the motor, the touchdown bearing and the casing followed.

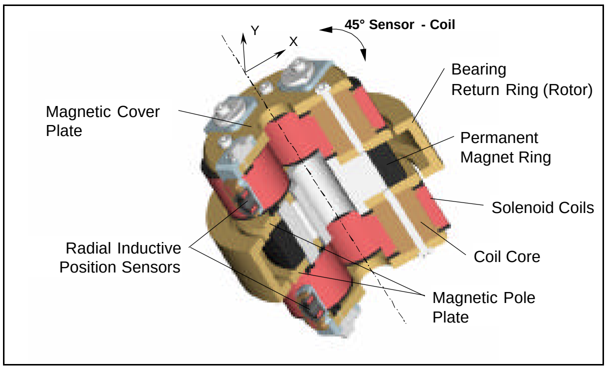

Figure 4: Magnetic Bearing with Sensor Assembly

The basic configuration of the magnetic bearing is depicted in Figure 4. It is similar to that of the AMSAT wheel [8] and the design proposed in [13]. Mainly because of the required diameter of 12 cm (see Table 2), other magnetic design variants for the bearing were rejected during the conceptual design phase. If the wheel diameter can be increased in the future due to a modified specification, other design variants with a better inertia-to-mass ratio could be considered.

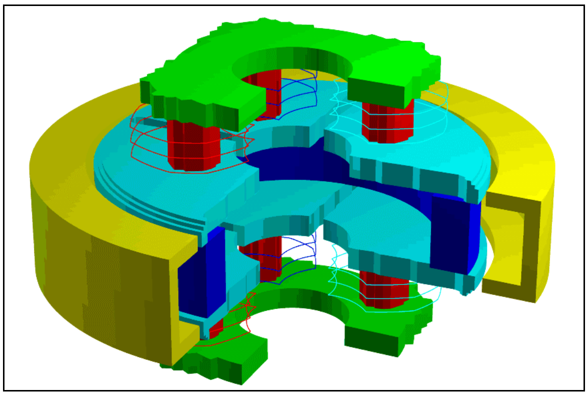

Figure 5: Magnetic Bearing Simulation Model

The magnetic design process was threefold:

- Controlled system design: equivalent network model [14] for understanding the magnetic circuit and parameter estimation using *MATLAB/ SIMULINK*. This model is a prerequisite for the controller design and can be extended to a dynamic model of the controlled magnet system in both axes.
- Conceptual analysis of different magnetic circuits with the fast and easy-to-use 2D FEM program *QuickField* [11]; decision about the chosen magnetic circuit and the main parameters.
- Detailed magnetic design with the 3D FEM software package *MAFIA* [16]; analysis of the advanced bearing model as shown in Figure 5 to define cross sections and detailed dimensions.

The algorithms of the *MAFIA* software are based on the Finite Integration Technique (FIT), which is a theoretical basis for solving Maxwell's equations in integral form. With the *MAFIA* package in version 4, all kinds of electromagnetic field problems can be analysed, ranging from static to very high frequency operation, even including space charge fields of free moving charges.

The magnetic finite element simulation allowed the rapid development of a first engineering model for the momentum wheel within a few months. To large extent, “trial-and-error” iterations using several breadboard models with time-consuming phases of manufacturing and testing could be suppressed. Properties like magnetic flux, force and stiffness parameters were obtained by simulation in relatively short time and with much higher accuracy than via any hand calculations. And most importantly, the function of the bearing design was validated in an early development state, where changes could be applied without great effort.

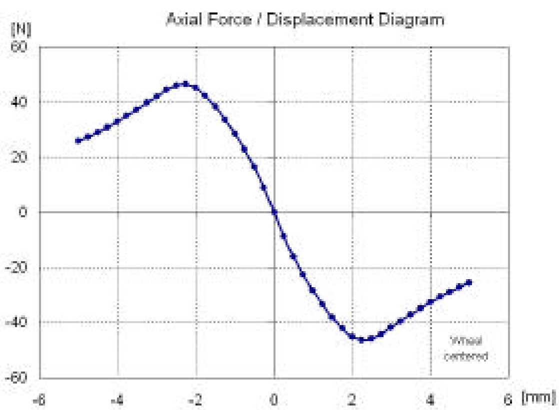

Figure 6: Axial Force vs. Displacement

Figure 6 shows the simulation results achieved for the axial direction of the bearing system. This diagram proves that the bearing can support the weight of the rotor under gravity conditions, although a small and unavoidable sag occurs which does not limit the operating and testing procedures in the laboratory. This sag, however, is not present in space and does not affect the wheel performance as it is taken into account for the bearing design.

In Figure 7, the radial bearing force vs. displacement is presented, with the coil’s Magneto-Motoric Force (MMF) as a parameter. The MMF is proportional to the coil current and the number of windings. When the wheel is switched off, the rotor rests in the touchdown bearings, which prevent the magnetic return ring (rotor element) from touching the magnetic pole plates (stator elements). This corresponds to a maximum displacement of 0.6 mm. When the magnetic bearing is switched on, the destabilising force of the permanent magnets has to be overcome by forces induced by the electromagnetic coils. If an MMF of 1800 or 2400 AW is applied, the restoring force is greater than the destabilising force. In this case, the rotor immediately levitates and is centred around the stator, such that the width of the air gap is circumferentially constant. The diagram proves that the bearing can be centred during lift-off. Furthermore, these diagrams reveal important information for dimensioning the control loop.

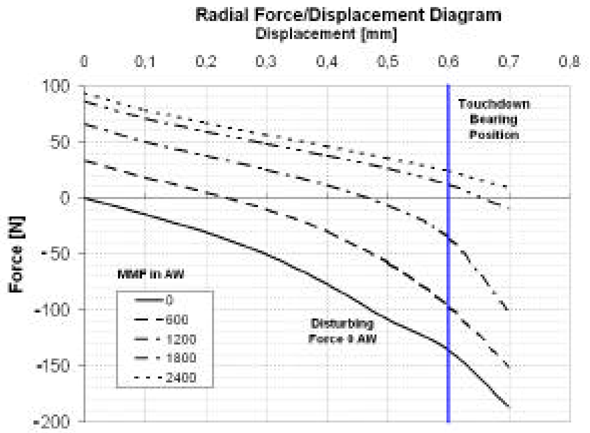

Figure 7: Radial Force vs. Displacement (Magneto-Motoric Force as parameter)

Due to the basic layout of the selected design, a coupling of the fluxes in both radial directions (x and y) exists. In the pole plates, this undesired coupling is restricted by using small connecting areas which will be saturated, and therefore limit the flux loss. However, in the cover plates, there are large coupling fluxes, which reduce the restoring force to obtain the ideally centred position of the wheel. Although this does not affect the function of the bearing, it increases the required power during lift-off and possibly during operation. This behaviour will be deeper analysed in the future and can be potentially optimised.

Control Engineering Aspects

As the magnetic bearing has active control in the two lateral axes, two independent servo loops are required. A block diagram of one of those control loops is given in Figure 8. Four sensors are used to measure the distance between the rotor and the stator of the wheel. Through the control loops, the inherent instability in those directions is compensated and a constant air gap maintained at all times. The time constant of the magnetic bearing control coils is long compared to the characteristic frequency ω_0 of the loop. The real control system is more complex than shown in Figure 8 and compensates for cross-coupling effects between the two axes and undesired tilt modes. The control electronics actively damp those modes and make the wheel unconditionally stable.

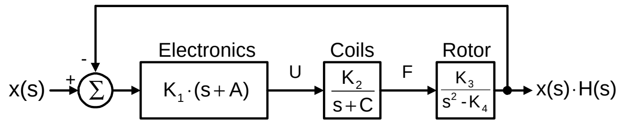

Figure 8: Bearing Control Loop (one axis)

The electronic circuit of the control loop is implemented purely analogue. In principle, a digital circuit could have advantages in terms of possible re-configuration regarding the control loop structure and its parameters, which would make the adjustment during the initial start-up easier. On the other hand, for a possible later qualification model, the necessary radiation hardened components are not easily available and would consume substantially more power than the present analogue circuit.

Sensor Aspects

A variety of position sensors are available for the detection of the rotor position. The selected type of position sensor must operate contactless. In addition, the sensors must resist the specified space environment with a large temperature range and feature a low phase shift over a wide frequency range. Candidate sensor types are capacitive sensors, Hall sensors, optical sensors, ultrasonic, and inductive sensors [12].

For reasons of radiation hardness, low sensitivity to ageing and the issues mentioned above, inductive (Eddy current) sensors were selected. Four of those sensors are used for sensing the rotor position and the tilt in each of the two lateral axes. They combine a small physical size with high resolution, excellent temperature stability and a small phase shift.

5. OVERALL WHEEL DESIGN

The mechanical design of the Compact Magnetic Bearing Wheel (CMBW) has been specifically aiming at the miniaturisation of the earlier configuration as built for AMSAT OSCAR 40, towards a version suitable for small and micro-satellites.

To achieve this goal, a survey on comparable ball bearing wheels was carried out, contributing to the definition of the key requirements in Table 2. The wheel design process itself is very much centred around the design of the magnetic bearing.
All drawings and FEM analyses were done with the 3D CAE software package *ProEngineer*.

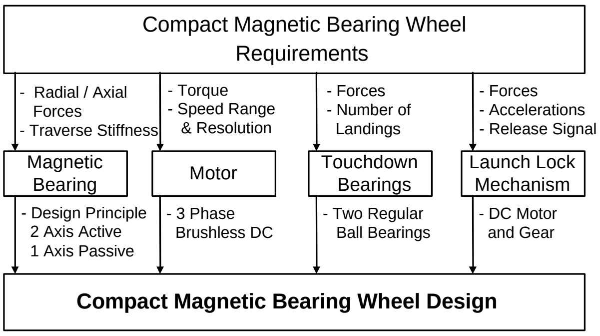

Figure 9: Wheel Assembly Main Components

The subassemblies of the wheel have been laid out following the general wheel requirements, where the magnetic bearing has a certain priority over the motor, touchdown bearing, and launch lock mechanism (see Figure 9). Secondary items have been adapted to the chosen design of the magnetic bearing.

Motor

The motor is a 3-phase brushless DC type, which is compatible with the space environment and the magnetic bearing as it works contact- and frictionless. For the conceptual motor design, the main objectives are:

- Small volume and mass
- Favourable mass distribution towards the outer rotor perimeter, increasing the rotor inertia
- Low power consumption

Table 4: CMBW Motor Requirements

Requirement	CMBW Motor
Continuous power	2 W @ 1000 rpm
Peak power	4 … 6 W @ 5000 rpm (max. speed)
Forward / Reverse operation	Yes
Motor / Brake operation	Yes
Power supply voltage	28 V DC
Control modes	Speed / Torque
Precision in closed-loop control	± 10 rpm / ± 0,05 mNm
Temperature control	Thermal conduction & radiation

In the chosen design, the motor coils are attached to the stator assembly, and the motor permanent magnets are arranged inside the rotor, close to the outer rim. This configuration concentrates the motor mass such that it adds as much as possible to the moment of inertia. When a current is applied to the motor coils, their magnetic field interacts with the magnetic field of the permanent magnets and a torque is applied, which accelerates or decelerates the wheel. The torque level is controlled through the motor drive electronics. Rare earth magnets (NdFeB) are applied as they substantially increase the motor performance compared to ferrite magnets.

Table 5: Motor Design Features

Feature	Motor Design
Magnet type	Sintered rare earth (NdFeB)
No. of phases	3 with bipolar driver
No. of poles	12
No. of coils per phase (slots)	3 coils per phase (9 over the circumference)
Max. speed	5000 rpm (± 1000 rpm)
Max. torque	15 mNm
Max. diameter	100 mm
Max. height	40 mm
Nominal air gap	5 mm

The magnetic circuit of the motor assembly has also been optimised with the magnetic finite element simulation program *QuickField* [11], thus determining the optimum amount of iron for the magnetic return ring avoiding undesired magnetic flux saturation. At the same time, the magnetic flux density could be increased, making the motor more efficient in terms of the torque-to-power ratio and its mass. The motor windings are embedded into a ring of composite material, which also holds a set of Hall-effect sensors to detect the magnet and rotor angular position for motor commutation and control. The chosen arrangement applies a symmetric torque and adds redundancy to the system.

The main characteristics of the motor are summarised in Table 5, and Figure 10 shows the motor assembly to be accommodated inside the wheel.

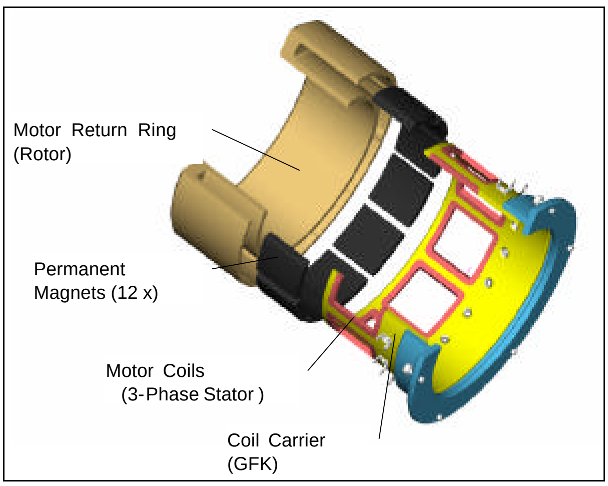

Figure 10: Motor Assembly

Touchdown/Emergency Bearings
The touchdown bearings shall prevent contact between rotating and non-rotating parts of the assembly if the magnetic bearing fails or if it is switched off. The touchdown bearings have to withstand high dynamic loads as the rotor may be at full speed in case of a failure. They are designed to prevent mechanical damage and deformation of the rotor and the magnetic bearing. Two dry-lubricated ball bearings act as touchdown/emergency bearings.

Launch Locking Device
A launch locking device shall protect the wheel during on-ground handling/transportation and the launch phase, and it shall release the rotor in orbit. Although the magnetic bearing as designed seems capable to hold the rotor during launch via the magneto-static forces induced by the permanent magnets, magnetic bearing wheels are normally equipped with an additional locking system (see e.g. [4]).

Aiming at compatibility with the present wheel design, the main functional performance requirements for the launch locking device have been defined as follows:

- Adequate protection of the rotor against adverse effects of launch, handling and transportation loads, e.g. plastic deformation or deterioration of the rotor balancing.
- Locking shall be assured without gapping separation between rotor and stator (i.e. the touchdown bearings) during the launch phase.
- Electric remote control of multiple locking and release cycles without manual interaction.
- Lifetime: 50 locking and release operations.
- Duration of a locking or release sequence: 10 min maximum.
- The required stroke of an axial device is > 2.0 mm, for a radial device it is > 0.8 mm (retraction beyond the position of the touchdown bearings).
- No maintenance/refurbishment during testing and ground life.
- Electric status monitoring (wheel locked/released).

The launch locking device will be structured in three major subassemblies (see also Figure 11):

- the actuator, which provides the necessary input force or movement
- the transmission system, which amplifies and/or transforms the provided actuator force/movement
- the mechanical rotor interface, where an output force is used to lock or clamp the rotor

Currently, the detailed design of the launch locking device is being established. For reversible operation, a DC motor has been baselined as actuator.

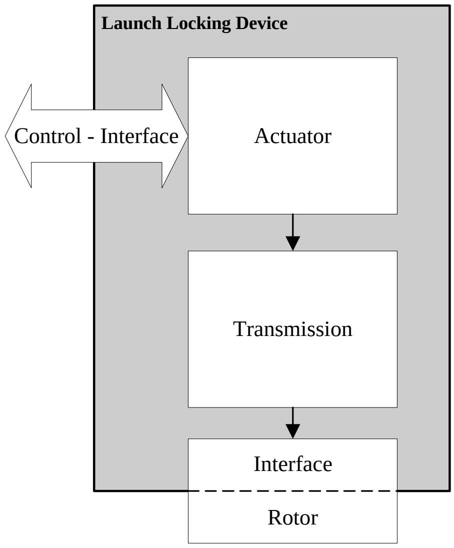

Figure 11: Launch Locking Device – Generic Structure

Control and Drive Electronics
The electronics design for the first prototype wheel is kept rather simple. Analogue electronics are used for the bearing control, and the motor will be supplied via an off-the-shelf electronics module. The digital command & telemetry interface is implemented with the help of a digital/analogue interface, which is driven by a PC. It is planned to integrate the electronics into the wheel housing in a later qualification model.

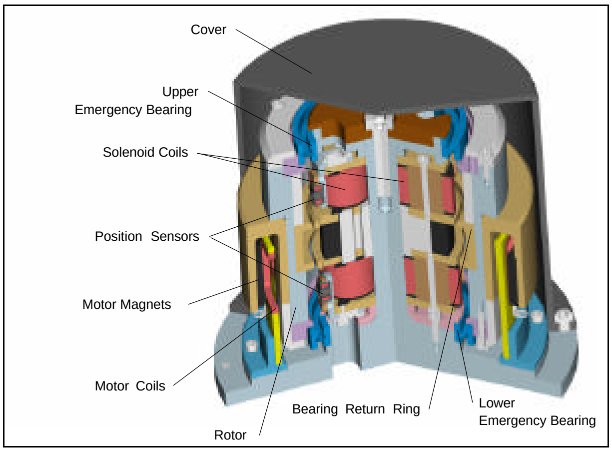

Figure 12: Wheel General Assembly

Overall Assembly
Figure 12 shows the wheel general assembly. The wheel consists of a centre mandrel, where the inner magnetic bearing unit (Figure 4) and the motor coil carrier (Figure 10) are mounted on. In a sandwich configuration, this subassembly contains the permanent magnet ring, the two pole plates below and above the ring, the solenoid coils for flux control and two magnetic cover plates at the top and the bottom. It also holds the eight rotor position sensors and the two touchdown bearings.

All flux-carrying parts of the central bearing subassembly are made of a cobalt-iron alloy, which has favourable properties regarding magnetic saturation effects, saving mass and volume. The outer bearing assembly consists of the magnetic bearing return ring and the motor return ring with its permanent magnets (see Figure 10). A cup-type housing fully encloses the wheel.

The wheel assembly is kept simple and modular as far as possible. It offers many similar mechanical parts and leaves some room for a later integration of the launch locking device. After assembly and sensors adjustment, the wheel will undergo a series of development tests (function, vibration & thermal environment).

6. CONCLUSIONS AND OUTLOOK

The presented design offers a favourable compromise between complexity and the benefits of magnetic bearings. Currently, a first prototype wheel is being assembled and will be tested soon. The development has demonstrated that magnetic bearing technology can be adequately miniaturised and has the potential to be used on small and micro-satellites.

The obtained simulation results allow very promising predictions for the performance of the hardware. Nevertheless, there might be some problems with flux coupling effects, which can be probably overcome by a more sophisticated design in the future. For a possible later qualification model, the electronics will have to be integrated into the overall design, together with an appropriate launch locking device. Furthermore, the electronics could be upgraded with an integrated micro-controller for motor commutation and speed control. Possibly, digital control could also be considered for the magnetic bearing.

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