Design And Development Of A Compact Magnetic Bearing Momentum Wheel For Micro And Small Satellites

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Abstract. Reaction and momentum wheels have become standard equipment for three-axis attitude stabilisation of conventional satellite classes as used e.g. 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 up to 100…200 kg with increasingly demanding requirements on attitude control.

Wheels suitable for small satellites have a typical momentum capacity up to approximately 0.4 Nms, and masses up to about 2 kg. All existing miniature wheels known to the authors are relying on ball bearings for rotor suspension, which may limit the lifetime of a particular mission or introduce undesired levels of micro-vibrations. Magnetic bearings have the potential to overcome those disadvantages. However, the design of a sufficiently small magnetic bearing with all the necessary components and sub-assemblies involves a number of technical challenges, which are discussed in detail.

The paper focuses on the magnetic bearing design process, using magnetic field CAE tools, and 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 will be described and an outlook for further improvements and potential future developments will be given.

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 distinctive advantages like virtually zero wear and extremely low friction losses. They do not suffer from stiction-friction effects common with mechanical ball bearings, making them ideal candidates for deep space missions with long hibernation periods, long lifetime requirements and wide operational temperature ranges. Furthermore, they are highly suitable for antenna fine pointing purposes on geostationary satellite missions where conventional bearing wheels may limit the satellite lifetime. Earth observation and science missions also can clearly benefit from their 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]. Mainly, one-axis and two-axis active control of magnetic bearings can be distinguished. 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 doing so, all three axis of a satellite could be controlled by just one wheel.

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 3-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 as challenging as for bigger satellites. However, the design, manufacturing and test efforts associated with magnetic bearings can be nowadays reduced by powerful software tools and state-of-the-art technologies, e.g. regarding the control electronics. 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.

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 shall be utilised as technology demonstration platform to validate new concepts for spacecraft autonomy. The satellite comprises a 600x600x800 mm box-shaped structure, and it has a mass of about 100 kg. 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 . As actuators, ball bearing wheels with 0.12 Nms momentum storage and 5 mNm torque capability are used in combination with magneto-torquers for wheel off-loading. 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.


Figure 1: AMSAT OSCAR 40 (Phase 3D)

Recently, first attempts have been made to apply magnetic bearing wheels also for small satellite projects. In close collaboration with AMSAT, the international amateur radio satellite corporation, three magnetic bearing wheels with 15 Nms momentum storage capacity and a mass in the order of 10 kg (including electronics) have been built[6], Fig. 2. They are presently flying on the AMSAT OSCAR 40 (Phase 3-D) satellite, which has a launch mass of approximately 500 kg, Fig. 1. Unfortunately, at the time of writing this paper, the wheels were not yet operational in flight, but experienced extensive ground testing.

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

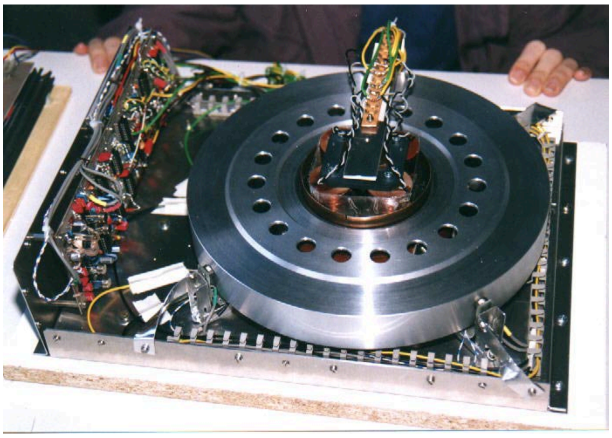
Figure 2: Laboratory Model of the AMSAT Magnetic Bearing Wheel.

Requirements for Small Satellite Missions

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 performances has been established, Table 1.

Table 1: Reference Satellite Performance

Feature	Performance
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

Table 2: Wheel Main Requirements

Feature	Nominal Target Performance
Angular momentum	0.2 Nms
Speed range	0-5000 rpm
Reaction Torque	10 mNm
Command Torque Res.	0.01 mNm
Operation Modes	Torque & Speed Loop
Speed Loop Accuracy	± 5 rpm
Operating Voltage	28V DC
Power Consumption	2.5 W steady-state @ 1000 rpm
	5 W steady-state @ max. speed
	20 W peak power
Weight	≤ 2 kg
Main Dimensions	12 cm Diameter 10 cm Height
Temperature Range	-30 … +50 ºC
Tachometer Signal	≈ 100 Pulses/Rev.
Static Imbalance	≤ 0.5 g*cm
Dynamic Imbalance	≤ 10 g*cm^2

Based on the platform performance as well as the experience with the AMSAT wheel, and utilising a simplified wheel and satellite dynamics model, the following main requirements have been derived for the prototype wheel envisaged , Table 2.

Magnetic Bearing Operation Principles

A completely passive and contactless magnetostatic bearing, stable in all 6 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 either control one, two or five DOF actively[8].

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

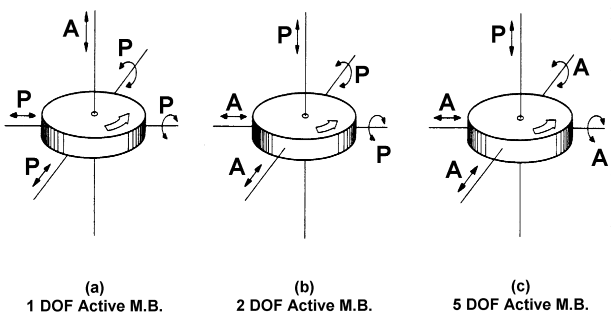

Figure 3: Basic Magnetic Bearing Principles

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 2 DOF option where the wheel is actively controlled along two orthogonal radial directions where 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 independently controlled by their 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 as parts of the bearing contribute to the momentum storage capacity. For position detection, magnetic field displacement type inductive sensors are mounted with 90 degrees angular spacing around the flywheel, facing the rim surface.

Table 3: Main Properties of the Different Principles

Number of actively controlled DOF	Bearing Properties
1 (axial)	Simple electronics, low power consum-ption but high axial dimensions, 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 less reliable than other options; offers vernier gimballing capability. Special pre-cautions 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 has the advantages of high reliability and low 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 the radial direction in the presence of imbalance or external forces.

Another advantage for the active control is the linearised characteristic of force vs. current through the superposition of two opposite directed reluctance forces. These forces are generated in the air gaps shown in Fig. 4, on the left and right hand side. Rare earth permanent magnets (NeFeBr) were chosen because they offer a high energy density and therefore have advantages in terms of mass and volume.

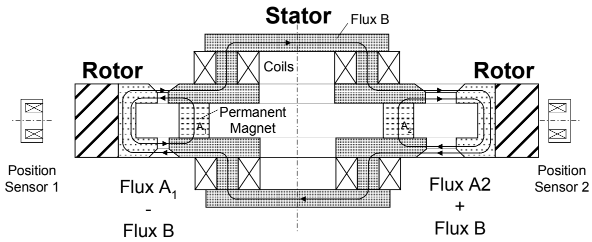

Figure 4: Schematic Cross Sectional View of the Magnetic Bearing

Figure 4 shows a cross section 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 center the flywheel.

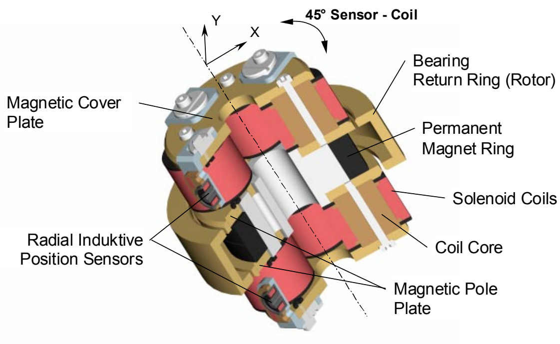

Figure 5: Magnetic Bearing with Sensor Assembly

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 and the mechanical dimensions.

The Magnetic Bearing Design

The baseline design concept of the compact magnetic bearing wheel is to save mass and achieve a high moment of inertia in the rotor. Therefore, the mass inside the rotor is concentrated towards the outer rim. Consequently, the motor magnets and the motor return ring as heavy parts have to be placed there. The magnetic bearing is placed in the centre of the wheel and was designed first. At a later stage, the motor, the touchdown bearing and the casing followed.

The basic structure of the magnetic bearing is shown in Fig. 4 and is similar to the AMSAT wheel[6] and the design wheel design by Studer[12]. Mainly because of the required diameter of 12 cm, cp. Table 2, other magnetic design variants of the developed bearing were rejected during the conceptional design phase. If the wheel diameter can be increased in future due to different specifications, other design variants which show a better mass vs. moment-of-inertia ratio can be considered as well.

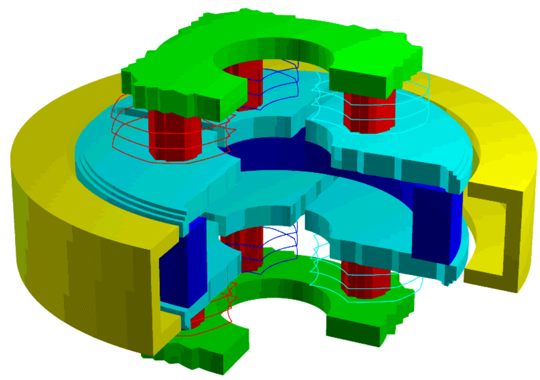

Figure 6: 3D Cross Sectional View of the Magnetic Bearing Simulation Model

The Magnetic Circuit Design

The magnetic design process was threefold:

- Controlled system design: magnetic equivalent network model[13] for understanding and parameter estimation using *Matlab/Simulink,* this model is a basis for the controller design and can be extended to a dynamic model of the controlled magnet in both axis
- Analysis of different magnetic circuits during conceptional design with the fast and easy useable 2D-FEM program *Quickfield*[10], decision about the chosen magnetic circuit and the main parameters
- Detailed magnetic design with the 3D Finite Integration Technique (FIT) software *MAFIA*[15], analysis of the bearing model shown in Fig. 6 to define cross sections and detailed dimensions.

For the detailed magnetic design of the magnetic bearing momentum wheel, the finite-element simulation software MAFIA was used. MAFIA's algorithms are based on the Finite Integration Technique (FIT) which is a theoretical basis for solving Maxwell's equations in integral form. With MAFIA 4, all kinds of electromagnetic field problems can be solved, ranging from statics to the highest frequencies, even including space charge fields of free moving charges. The magnetic finite element simulation allowed the rapid development of one engineering model of the momentum wheel within a few months. No “trial-and-error” method with many breadboard models, long workshop and testing periods was necessary to validate the design. Properties like magnetic flux, force and stiffness parameters were obtained in a relatively short time from the simulations with much higher accuracy than by hand calculations. Most important, the principal function of the bearing design was validated in an early development state, where changes could be applied without great effort.

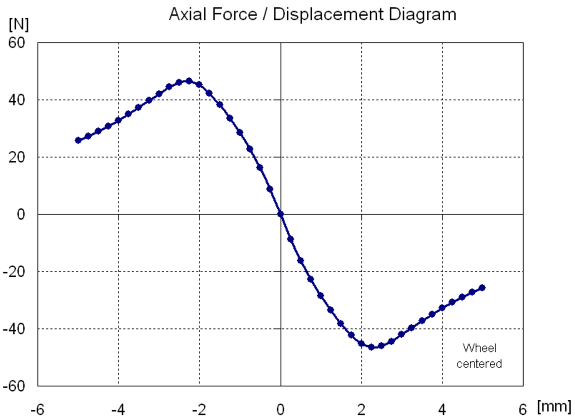

Figure 7: Axial Force vs. Axial Displacement

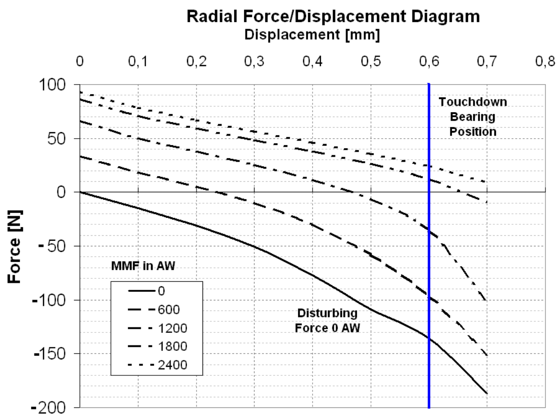

Figure 8: Radial Force vs. Displacement; Parameter Coil Current.

Figure 7 shows the simulation results achieved in axial direction of the bearing structure. 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 the bearing design takes care of it.

In radial direction, Fig. 8, the radial bearing displacements vs. the force is shown, with the coil magneto motoric force (MMF) as a parameter. The MMF is proportional to the coil current and the number of wire turns. When the wheel is switched off, the rotor resides in the touch down bearing, which prevents the magnetic return ring (rotor element) from touching the magnetic pole plates (stator element). This corresponds to a displacement of 0.6 mm. When the bearing is switched on, the destabilising force of the permanent magnets has to be overcome by forces induced by the electromagnetic coils. The resulting force has to be positive. In this case, the rotor immediately levitates and can be centred by the control loop around the stator, such that the width of the air gap is circumferentially constant. The diagram proves that the bearing can be centered during lift-off. Also, these diagrams reveal important information for dimensioning the control loop.

Due to the principal structure of this design a coupling of the flux in both radial axes (x and y) exists. In the pole plates this undesired coupling is restricted 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 ideal centred position of the wheel. Although this does not harm the operation of the bearing, it increases the required power during lift-off and possibly during operation. This behaviour will be analysed deeper in future and has the potential to be optimised.

Control engineering aspects

As the magnetic bearing has active control in two lateral axes, two independent servo loops are required. A bock diagram of one of those control loops is shown 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 above and compensates for cross-coupling effects between the two axes and undesired tilt modes. The control electronics actively damps those modes and makes the wheel unconditionally stable.

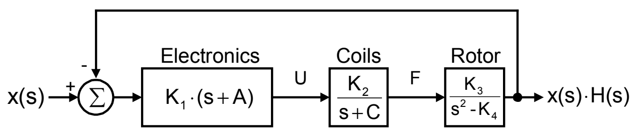

Figure 9: Approximation of the Control Loop, One Axis

The electronic circuit of the control loop is implemented purely analogue. In principle, a digital circuit has advantages in being reconfigurable in terms of the 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 actual analogue circuit.

Sensors

A variety of position sensors are available for the detection of the rotor position. The selected type of position sensor must operate contactless. Also, the sensors must resist the extreme space environment with its high temperature changes and feature a low phase shift over a wide frequency range. Available sensor candidates for selection are capacitive sensors, Hall sensors, optical sensors, ultrasonic and inductive sensors[11]. For reasons of radiation hardness, their insensitivity to ageing and the reasons 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.

The Wheel Assembly

The mechanical wheel design focuses on miniaturising the former design of AMSAT OSCAR 40 towards a smaller version suitable for small and microsatellites. To achieve this objective, a survey on suitable ball bearing wheels was carried out to establish the parameters given in Table 2. The design process itself is centred around the design of the magnetic bearing. All drawings and FEM analyses were done with the 3D CAE software package ProEngineer.

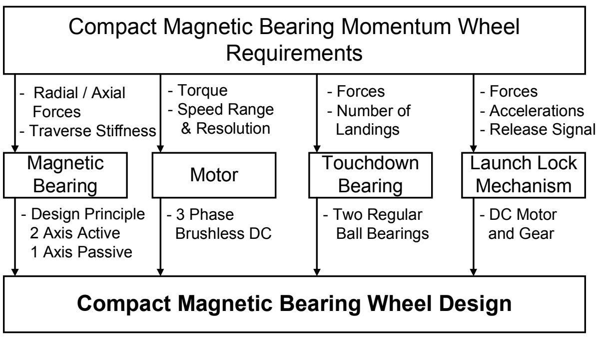

Figure 10: Wheel Assembly Components.

The subassemblies of the wheel are laid out following the general wheel requirements, where the magnetic bearing has priority over the motor, the touchdown bearing, and the launch lock mechanism, Figure 9. Devices are adapted to the chosen design of the magnetic bearing.

Motor

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

- Small volume and mass
- Favourable mass distribution towards the outer rotor perimeter, adding to it's inertia.
- Low power consumption

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 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 electronics. Rare earth magnets (NeFeBr) were used as they substantially increase the motor performance compared to ferrite magnets.

The magnetic circuit of the motor assembly was optimised with the magnetic finite element simulation program Quickfield[10], thus optimising the amount of iron for the magnetic return ring without the danger of 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 as well as saving mass.

The motor windings are embedded into a ring of composite material, which also holds a set of hall sensors to sense the magnet position for the motor electronics. This arrangement applies a symmetric torque and adds redundancy to the system.

Table 4: CMBW Motor Requirements

Requirement	Value CMBW-Motor
Continuous power and torque requirement	2 W @ 1000 rpm
Peak power and torque requirement	4 W @ 5000 rpm (max. speed)
Forward / Reverse operation	Yes
Motoring / braking operation	Yes
Power supply voltage	28V
Type of control required	Speed / Torque
Precision in close-loop control	± 10 rpm / ± 0,05 mNm
Temperature control	Thermal conduction & radiation only

Table 5: Motor Design Features

Feature	Value
Magnet type	Sintered rare-earth (NdFeB)
No. of phases	3 with bipolar drive
No. of poles	12
No. of coils per phase (slots)	3 coils per phase (9 over the circumference)
Maximum Speed	5000 rpm (+/- 1000)
Max. Reaction Torque	15 mNm
Max. diameter	100 mm
Max. height	40 mm
Air gap	5 mm

The main features of the motor are summarised in Table 5 and Figure 10 shows the motor assembly inside the wheel.

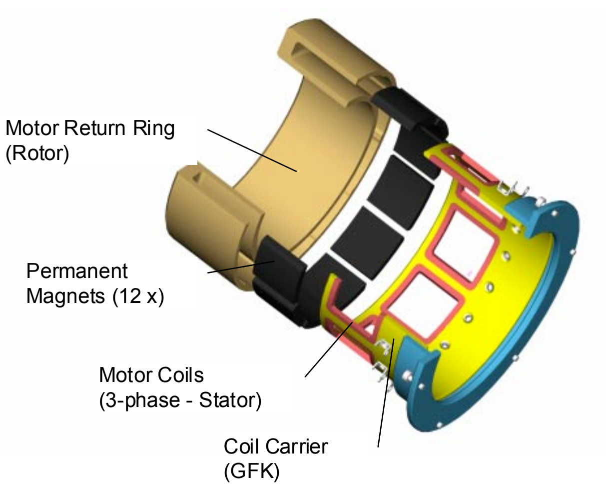

Figure 11: Motor Assembly

Touchdown Bearings

The touchdown bearings 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 emergency bearings.

Launch Locking Device (LLD)

A launch locking device protects the rotor against damage during the launch phase and releases it in orbit. Although a magnetic bearing seems capable to hold the rotor during launch by magnetostatic forces induced by the permanent magnets, most commercially available magnetic bearing flywheels are equipped with an additional locking system.

An attempt was made to develop such a mechanism in first defining the requirements, making a selection of conceivable LLD principles, choosing a design and then doing the calculations and drawings. The first prototype will not include the LLD but it will possibly be implemented in a later qualification model of the wheel.

The launch locking device is structured in three major subassemblies:

- The actuator, which provides the necessary force or movement;
- the transmission system, which amplifies and/or transforms the provided force/movement;
- the mechanical interface, where a force is used to lock (clamp, etc.) the rotor.

The functional performance requirements describe the essential parameters of the LLD performance:

1. Live cycle requirement: 50 locking and release operations;
2. Electric remote control of multiple locking and release without manual interaction;
3. Duration for a locking and release sequence max. 10 min.
4. Protection of the rotor against damage during the launch, e.g. plastic deformation or deterioration of the balancing.
5. Locking shall be assure that no gapping separation between the rotor and stator (emergency bearing) occurs during the launch phase.
6. The required stroke of an axial device is > 2.0 *mm*, for a radial device it is > 0.8 *mm* (retraction beyond position of the emergency bearing).
7. No maintenance during testing and ground life.
8. Electric status monitoring (locked/released).
9. Compatibility with the existing wheel design
10. No major wheel design change tolerated.

The chosen implementation of the LLD consists of a DC-motor as an actuator, gears, a screw and a clamping mechanism with a spring. The motor drives the gears, which transform the torque to the clamping mechanism. The clamping mechanism is mounted on the nut of a screw that transforms the rotational motion into a translational one which in turn holds down and releases the rotor.

Electronics:

The electronics design for the prototype wheel is kept simple. Analogue electronics is used for the bearing control and an off-the-shelf electronics module for the motor. The digital interface is implemented with the help of an digital/analogue interface which is driven by a PC. It is planned to integrate the electronics into the wheel casing in a later qualification model.

Overall Assembly:
Figure 11 shows the overall wheel assembly. The wheel consists of a central spike, where the inner bearing unit, Fig. 5, and the motor coil carrier, Fig. 11, are mounted on. In a sandwich configuration, the inner part of the bearing unit contains the permanent magnet ring, below and above the two pole plates, the solenoid coils for flux control and two magnetic cover plates as the top and the bottom.

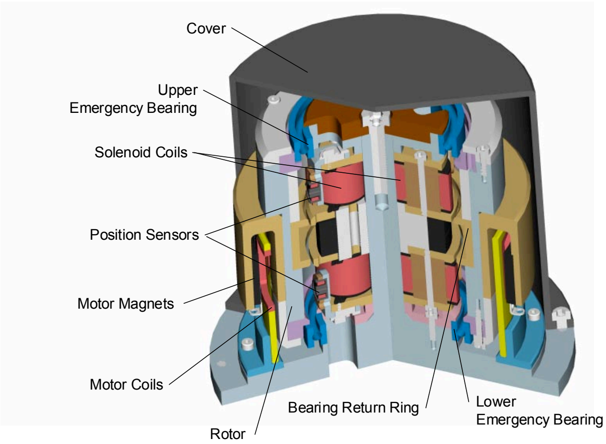

Figure 12: Cross-section Through the Overall Wheel Assembly

It also holds the 8 rotor position sensors and the two touch down 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 which is part of the rotor. The rotor also contains the motor return ring with its permanent magnets, Fig. 11. A cover protects the rotor from its environment.

The wheel assembly is kept simple and modular. It offers many similar mechanical parts and leaves some room for a later integration of the launch locking device. The wheel will be tested (function, vibration, thermal) after it is assembled and the sensors are adjusted.

Conclusions and Outlook

The presented design offers a favourable compromise between complexity and the benefits of magnetic bearings. Being compatible in terms of mass and volume, it still requires more DC power and may require more efforts in assembling. At the time of writing this paper, a prototype wheel is being assembled and will be tested soon. The test results will be given in summary report, available from ESTEC at the end of 2001.

The simulation results show promising results for the tests, but show problems with flux coupling effects, which can be overcome by a more complex design in the future. In a possible later qualification model, the electronics will have to be integrated into the mechanical design together with the suggested launch locking device. Also, the electronics could be upgraded with an integrated micro controller for controlling the motor commutation and speed and possibly a DSP for the magnetic bearing control loops. The presented compact magnetic bearing momentum wheel shows that magnetic bearing technology can be miniaturised and has the potential to be used on small and micro satellites.

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