DEGREE PROJECT

Reaction Wheel Performance Characterisation and Assessment of Electromagnetic Interactions with Magnetic Torquers

Leonie Sander

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Luleå University of Technology
Department of Computer Science, Electrical and Space Engineering
Abstract

Having an in-depth knowledge on the performance characteristics of space mechanisms in flight operation, with special attention to nominal vs. anomalous performance, is vital for mission success. On many unmanned spacecraft for Earth observation missions, reaction wheel assemblies are used in combination with magnetic torquers for their attitude control. Understanding the magnitude of potential electromagnetic interactions between both types of attitude control actuators is of particular interest for large spacecraft as they are usually equipped with strong magnetic torquers. In this frame, experimental investigations have been performed on simplified test set-ups with flight representative reaction wheel assemblies operated in external homogeneous magnetic fields as well as in close vicinity of magnetic torquers which create inhomogeneous magnetic fields. The test results have been successfully correlated with computer-based simulation output obtained from models with different levels of complexity. The impact of critical parameters like the location of magnetic torquers relative to reaction wheels and their material properties such as electrical conductivity and magnetic permeability have been particularly studied. It has been found that magnetic torquers pointing orthogonal to the reaction wheel spin axis cause the highest influence on the reaction wheel’s performance characteristics. The material choice for the flywheel rotor, being either ferromagnetic or paramagnetic, has a strong influence when exposing the reaction wheel assembly to external magnetic fields. In general, the increase of loss torque noticed with all reaction wheels tested has been caused by eddy current effects. In this frame, the impact of using ferromagnetic materials has been surprisingly strong. Specifically, the local distortions and guidance of the magnetic field due to ferromagnetism has a highly amplifying effect on eddy currents. However, interestingly it has also been found that the impact of material choice is much more severe when considering homogeneous magnetic fields and strong magnetic torquers while being less important with relatively small magnetic torquers. The main reasons for this finding have been compensating effects of ferromagnetic vs. highly conductive materials.
Résumé

Une connaissance approfondie des caractéristiques de performance des mécanismes spatiaux en vol, et plus particulièrement des performances nominales comparées aux performances anormales, est d’importance vitale pour la réussite d’une mission. Pour les missions d’observation de la Terre, la plupart des engins spatiaux non habités sont équipés d’ensembles de roues de réaction ainsi que de magnéto-coupleurs pour le contrôle d’attitude et la stabilisation. Comprendre l’ampleur des interactions électromagnétiques potentielles entre les deux types de capteurs de contrôle d’attitude est particulièrement pertinent pour les engins spatiaux de grande taille car ceux-ci sont généralement équipés de puissants magnéto-coupleurs. Dans ce cadre, des études expérimentales ont été réalisées sur des bancs d’essais simplifiés avec des ensembles de roues à réaction représentatifs du vol fonctionnant dans des champs magnétiques externes homogènes ainsi qu’à proximité immédiate de coupleurs magnétiques (champs magnétiques hétérogènes). Les résultats des tests ont été corrélés avec succès grâce à des simulations informatiques sur des modèles présentant différents niveaux de complexité. L’influence de paramètres critiques comme l’emplacement des magnéto-coupleurs par rapport aux roues de réaction et leurs propriétés matérielles telles que la conductivité électrique et la perméabilité relative ont été particulièrement étudiés. Il a été établi que les couples magnétiques pointant orthogonalement à l’axe de rotation de la roue de réaction ont le plus d’influence sur les caractéristiques de performance des roues de réaction. Le choix du matériau pour le rotor de volant, c’est à dire ferromagnétique ou paramagnétique, a une forte influence si l’ensemble de roue de réaction est exposé à des champs magnétiques externes. En général, l’augmentation de la perte de transfert de couple constatée avec toutes les roues de réaction testées a été causée par les effets de courants de Foucault. Dans ce cadre, l’influence des matériaux ferromagnétiques a été étonnamment forte. En effet, les distorsions qui en résultent et le guidage du champ magnétique amplifient fortement les courants de Foucault. Cependant, il a été constaté que l’effet du choix du matériau est beaucoup plus important si l’on considère des champs magnétiques homogènes et des grands coupleurs magnétiques. Toutefois, cet effet est moins important avec des petits coupleurs magnétiques.
Acknowledgements

I express my sincere gratitude to my supervisor René Seiler for his guidance throughout my internship. His expertise and invaluable guidance added considerably to my knowledge and experience in space mechanisms. I would also like to thank Lionel Gaillard, for welcoming me in the Mechanisms section at ESA/ESTEC, and thank you to all the team members in the department, especially Stefan Heindel and Anders Kjaer, for making this internship a very pleasant experience. I am highly thankful to Peter von Ballmoos and Dr. Victoria Barabash for providing me the opportunity to be a part of the M2TSI and SpaceMaster program.
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<td>Attitude Determination and Control System</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>DOFs</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
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<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>MCF</td>
<td>Mobile Coil Facility</td>
</tr>
<tr>
<td>MOI</td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>MTQ</td>
<td>Magnetic Torquer</td>
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<tr>
<td>RW</td>
<td>Reaction Wheel</td>
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<td>RWA</td>
<td>Reaction Wheel Assembly</td>
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Nomenclature

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<thead>
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<th>Symbol</th>
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<tbody>
<tr>
<td>(\omega)</td>
<td>Angular velocity</td>
</tr>
<tr>
<td>(\tau_{\text{Loss}})</td>
<td>Loss torque of reaction wheel</td>
</tr>
<tr>
<td>(\tau_{\text{RW}})</td>
<td>Reaction torque of reaction wheel</td>
</tr>
<tr>
<td>(B)</td>
<td>Local magnetic flux density</td>
</tr>
<tr>
<td>(B_{\text{MTQ}})</td>
<td>Magnetic flux density of magnetic torquer</td>
</tr>
<tr>
<td>(d)</td>
<td>Distance between magnetic torquer and reaction wheel</td>
</tr>
<tr>
<td>(F_L)</td>
<td>Lorentz force</td>
</tr>
<tr>
<td>(H)</td>
<td>Angular momentum</td>
</tr>
<tr>
<td>(I)</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>(M)</td>
<td>Magnetisation vector</td>
</tr>
<tr>
<td>(m)</td>
<td>Magnetic dipole moment</td>
</tr>
<tr>
<td>(n)</td>
<td>Number of windings in coil</td>
</tr>
<tr>
<td>(R)</td>
<td>Radius of coils</td>
</tr>
<tr>
<td>(T_{\text{ms}})</td>
<td>Magnetic stress tensor</td>
</tr>
<tr>
<td>(V)</td>
<td>Volume</td>
</tr>
<tr>
<td>(v)</td>
<td>Local velocity vector</td>
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1 Introduction

On most unmanned spacecraft, reaction wheel assemblies (RWA) are used as main actuators for three-axis attitude control such as for manoeuvres and the stabilisation of platform pointing. Therefore, a detailed knowledge of reaction wheel (RW) performance characteristics is needed for the monitoring of their operation over many years.

As a key indicator for the health status of RWs, the friction or loss torque characteristic is often estimated and monitored during on-ground testing and in-flight operation. A number of internal factors, such as the friction torque of the ball bearings used for flywheel suspension, are contributing to the total loss torque of conventional RWs. However, there can be other internal and external effects on the total loss torque, which have to be known and quantified in the frame of flight hardware health monitoring and anomaly investigations.

Acknowledging that current space missions can last as long as 15 years, and in some cases even longer, in-flight anomalies may become more likely due to some accumulated long-term degradation of mechanisms equipment, which might require intervention by spacecraft operators. Reaction wheel in-flight anomalies can be mission critical. In previous instances, they were often associated with erratic, rather fast and unpredictable changes of the friction torque.

For many spacecraft in Low Earth Orbit (LEO) missions, RWs are often used in combination with magnetic torquers (MTQs) as complementary actuators, which interact with the Earth’s magnetic field to exert a controlled torque on a satellite. The limited space on most spacecraft often means that these two actuator types are positioned in close vicinity to each other. The magnetic field generated by a MTQ can reach significant magnitudes at the location of a RW, for instance up to 3 mT on ESA’s Meteorological Operational Satellite - Second Generation (MetOp-SG). In a previous test campaign at ESA/ESTEC, it has been found that external magnetic fields can cause a loss torque increase by magnitudes similar to those of the internal friction losses. This interaction and the involved physical phenomena, along with a quantitative analysis and prediction, are not fully understood yet.

Over recent years, the performance characteristics of RWs have been investigated at ESA/ESTEC in close cooperation with industrial partners, in the context of several flight projects as well as research and development activities. In 2018, a first set of experimental tests has been conducted at ESTEC in order to quantify the effects of an external homogeneous magnetic field on RW performance.

1.1 Problem Statement

With regards to the effects by external magnetic fields, the real physical mechanisms causing a significant loss torque in reaction wheels is still fairly unknown. Therefore, this thesis aims to shed more light on the reasons and physical phenomena causing deviations from nominal performance. Based on the issues previously mentioned, this leads to the following problem statement:

*How and with what severity do external magnetic fields affect reaction wheel performance, and how can this be proven using laboratory tests and computer-based analysis?*

In order to answer above problem statement, a comprehensive investigation has been pursued and is summarised in this thesis, covering the following main steps and aspects:
1. Hardware test activities in the Mechanisms Laboratory (Hands-On Facility) at ESTEC, using the Herschel flight spare reaction wheel type RSI 20-215/18, a second test RW with type RSI 25-75/60 and the CryoSat Flight Spare magnetic torquer type MT30-2-GRC. Complementary tests in the ULYSSES Mobile Coil Facility (MCF) at ESTEC, using the RSI 25-75/60 test wheel. The following main aspects are covered:

- Measurement of loss torque characteristics as function of rotation speed, magnetic flux density and magnetic field orientation being orthogonal or parallel to the RW’s spin axis.
- Identification of the additional resistive torque caused by the external magnetic field.

2. Establishment of a computer-based performance model for the simulation of relevant operating conditions in the experimental tests and investigation of the underlying physical effects using MATLAB, the Computer Aided Design (CAD) software SolidWorks, and the Finite Element Modelling (FEM) software COMSOL Multiphysics. The models shall comprise the following magnetic field sources and hardware:

- Homogeneous magnetic field created by the Helmholtz Coils of the ULYSSES Mobile Coil Facility as used for the RW RSI 25-75/60 and during an earlier related test campaign on the Herschel flight spare RW.
- Inhomogeneous magnetic field created by a representative MTQ.
- Simplified reaction wheel assembly.

3. Correlation of the COMSOL modelling and simulation output with previously obtained and new experimental test results. Conclusions on the underlying physical phenomena.

Within the investigation, the tasks as shown in Figure 1 have been followed. The box highlighted in grey has been an additional task that does not directly contribute to the main topic, however it has been followed as side project currently relevant in the overall context of RW technology at ESA. In this frame, an iPhone app has been developed using the programming language Python with the aim of detecting the spin direction of RWs via measurements of the magnetic field generated by their internal motor sub-assembly.

Throughout the investigation, the experimental tests and the simulations have been conducted in parallel and iterative, despite the rather ‘linear’ and sequential paths shown in the figure above.
2 Scientific and Engineering Background

A reaction wheel based Attitude Determination and Control System (ADCS) of a spacecraft is mainly responsible for the angular orientation and pointing of the main platform including the payload by means of angular momentum control. In this context, external disturbance torques for instance due to solar particle and radiation pressure or atmospheric drag, have to be compensated. Nevertheless, there can be spacecraft internal sources of disturbance, for instance undesired and unpredictable rapid changes of the friction torque induced by RW ball bearings. In this chapter, the fundamental design and operating principles of reaction wheels and magnetic torquers will be described as they are commonly used in the ADCS of LEO satellites.

2.1 Reaction Wheels

A reaction wheel assembly comprises a flywheel used by a spacecraft’s attitude control for the management and exchange of angular momentum. There are three main categories of flywheel based actuators used by the ADCS:

1. Momentum Wheels: Flywheel assemblies typically operated around a predefined bias speed.
2. Reaction Wheels (RWs): Flywheel assemblies that can be spun up or down over a large speed range and in both directions.
3. Control Moment Gyroscopes (CMGs): Flywheel assemblies mounted on single-gimbal or in rare cases dual-gimbal stages for exerting a high gyroscopic output torque on a spacecraft. Mostly for increased agility of the platform.

This thesis solely focuses on reaction wheels. As basic functional principle, a spacecraft will counter-rotate according to the direction and magnitude of the total reaction torque exerted by the cluster of RWs operating on a spacecraft, by conservation of the total angular momentum in free space.

The vast majority of spacecraft use conventional RWs, which are based on flywheel rotors suspended by mechanical ball bearings and actuated by an electric motor, which is often a brushless DC motor, either in a hermetically sealed housing or vented during spacecraft launch. A simplified cross-section of such RW assembly is shown in Figure 2. It consists of a rotating flywheel and stationary sub-assemblies including a housing, drive electronics, etc. The commonly used brushless DC motors are constructed in a way that the electrical coils are on the stator and the permanent magnets on the rotor. Concluding from previous investigations, the stator part of the motor has a negligible influence on the aspects addressed in this thesis. [1]. Therefore, it will not be discussed further.

RWs can be rotated in either direction and at a speed within the entire specified range in response to the commands sent by the spacecraft’s ADCS. Typically, RWs are operated well above a minimum speed in order to avoid nonlinear performance due to stiction and other low-speed effects.
Optionally, they can be operated at a near-constant rotation speed in order to generate a bias angular momentum. In this way, a spacecraft axis can be pointed in an inertially fixed direction and thus lowering the impact of external disturbance torques. The reaction torque $\tau_{RW}$ generated by a flywheel can be evaluated as a change in angular momentum $H$ over time:

$$\tau_{RW} = \frac{dH}{dt} \quad (1)$$

The angular momentum is the product of the flywheel’s Moment of Inertia (MoI) $I$ around the spin axis and the angular velocity $\omega$:

$$H = I \omega \quad (2)$$

The MoI is dependent on the geometry and mass distribution of the flywheel, thus a higher angular momentum can be achieved via higher rotation speeds and/or an optimised mass distribution, preferably with more mass at a large distance from the spin axis. [2, 3]

An important design aspect is found with the choice of flywheel material, in the specific cases aluminium or steel. In this thesis, the performance characteristics of two RW types by Collins Aerospace / Rockwell Collins Deutschland have been studied, which will be referred to as RW A and RW B throughout this thesis. Their relevant design characteristics are shown in Table 1. While slightly differing in design and performance, the comparison of an aluminium and a steel reaction wheel is ideal for identifying the governing physical phenomena when the effects of an external magnetic field are to be analysed.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RW A</th>
<th>RW B</th>
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<tr>
<td>Type</td>
<td>RSI 25-75/60</td>
<td>RSI 20-215/18</td>
</tr>
<tr>
<td>Flywheel rotor material</td>
<td>Aluminium</td>
<td>Steel</td>
</tr>
<tr>
<td>Max. speed [rpm]</td>
<td>6000</td>
<td>2700</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>308</td>
<td>345</td>
</tr>
<tr>
<td>Max. reaction torque [mNm]</td>
<td>75</td>
<td>215</td>
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### 2.2 Magnetic Torquers

A magnetic torquer is an attitude control actuator, which can be used for momentum off-loading, furthermore detumbling and general stabilisation of spacecraft. The magnetic dipole field generated by the torquer interacts with an external magnetic field, usually the Earth’s magnetic field, and is thereby able to exert a control torque on a spacecraft.

A MTQ as depicted in Figure 3 is typically rod-shaped and mainly comprises wire coils on a ferromagnetic core. Commonly, it features two coils for redundancy wound on a high-permeability core material. It generates an magnetic dipole when powered with a controlled current, and it tends to align with the Earth’s magnetic field due to the resulting torque. The mounting locations of MTQs should preferably be far from instruments and equipment sensitive to magnetic fields as well as from other MTQs in order to avoid cross-coupling.
The generated magnetic dipole moment $m$ depends on several design parameters, such as the coil dimensions, number of windings, the applied current and the core material properties. When interacting with the Earth’s magnetic field, a torque $\tau_{MTQ}$ on the spacecraft is generated:

$$\tau_{MTQ} = m \times B$$

where $B$ is the local flux density of the Earth’s magnetic field. MTQs are typically used on spacecraft in relatively low altitude orbits as the magnetic field of the Earth rapidly decreases with distance and thus, results in less torque $\tau_{MTQ}$ with increasing altitudes [3].

Within this investigation, the CryoSat flight spare MTQ by ZARM Technik GmbH has been used to generate a magnetic field in proximity of the respective reaction wheels. The specific MTQ is designed to reach a magnetic dipole moment of up to $\pm 30$ Am$^2$ at an input current of $\pm 120$ mA. MTQs can vary significantly in their size and, thus, in their generated magnetic dipole moment. Typically, larger spacecraft require stronger MTQs as shown in Table 2.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Dipole Moment [A/m$^2$]</th>
<th>Unit Length [mm]</th>
<th>Unit Mass [kg]</th>
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<tbody>
<tr>
<td>CryoSat</td>
<td>$\pm 31$</td>
<td>380</td>
<td>1.4</td>
</tr>
<tr>
<td>Jason-CS</td>
<td>$\pm 140$</td>
<td>715</td>
<td>3.5</td>
</tr>
<tr>
<td>MetOp-SG</td>
<td>$\pm 400$</td>
<td>750</td>
<td>11</td>
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### 2.3 Electromagnetic Interactions

Reaction wheels need to be used in combination with external torque devices, for instance magnetic torquers, for momentum off-loading in order to avoid reaching the saturation wheel speed. Especially for large spacecraft and, thus, strong MTQs, the question arises if there can be undesired interactions between a MTQ’s dipole field and a RW potentially leading to an increased loss power and resistive torque. The locations of MTQs and RWs on a representative spacecraft are shown in Figure 4. In this specific case, the spacecraft has three MTQs and six RWs.

In a previous investigation by ESA’s industrial partners, it has been found that the RWs might experience a loss torque of up to $13$ mNm due to the MTQs with a magnetic dipole moment of $400$ Am$^2$ each. The MTQs might generate a magnetic field of up to $1$ mT at the location of the RWs. The loss torque effect has been estimated based on measurements in the BIOT facility at CNES Toulouse generating $3$ mT magnetic flux density at the RW’s rim, causing $29$ mNm resistive torque. Based on these findings, it was estimated that a flux density of $1$ mT would cause approximately $13$ mNm while assuming an almost linear relation between magnetic flux density and loss torque.
In order to fully understand the physical phenomena and quantitative losses, four different main scenarios have been studied in this thesis. The first two comprise of a homogeneous external magnetic field surrounding the complete RWA as shown in Figure 5a and 5b. The other two scenarios include an inhomogeneous external magnetic field generated by a dipole in proximity of an RWA as depicted in Figure 5c and 5d. The location of the MTQs with respect to the RWs can significantly vary among different spacecraft. Therefore, the orientations of the magnetic field sources pointing towards the RWA have been defined in axial and radial directions, with varying distances from the RW’s spin axis.
3 Experimental Investigations

Multiple experiments with different boundary conditions and parameters, such as rotation speed of the reaction wheels or magnitude of the ambient magnetic flux density have been performed. In a first step, the nominal behaviour of the RW without any additional external magnetic field has been determined. After that, the RWs have been operated in an external homogeneous magnetic field, followed by another test set-up with a magnetic torquer in the immediate vicinity of the RWs. An overview of the test set-ups together with the experimental test results are presented in this chapter.

3.1 Test Set-Up

The loss torque used to monitor the behaviour of the reaction wheel during operation is estimated using motor current, motor constant and reaction torque on the basis of the measured speed change as a function of time. The RW control software provided by Rockwell Collins Deutschland calculates the loss torque in real time and does not require any additional sensor information such as a torque transducer. The wheels have been studied in two different magnetic environments as described in this section.

3.1.1 External Source - Helmholtz Coils

The Helmholtz coils of the ULYSSES Mobile Coil Facility at ESA/ESTEC are used for generating a region of a nearly uniform static magnetic field. In the frame of space projects, Helmholtz coils are often used to demagnetise equipment items or to cancel external magnetic fields such as the Earth’s magnetic field for sensitive measurements. As shown in Figure 6, the MCF consists of three pairs of square Helmholtz coils. Out of these, two coil pairs can be used to compensate for the Earth’s magnetic field since the main axis of the facility is aligned with the direction to the magnetic North pole, and therefore no compensation is needed in East-West direction.

For the tests conducted in this investigations, only the third pair of coils has been utilised as highlighted in Figure 6. This coil pair is normally used for demagnetisation, but in this case they will be utilised to create a strong homogeneous magnetic field around the RWs [4]. The RW under test has been placed in the middle of the two parallel deperm coils.

Figure 6: Test set-up with RW A in the Mobile Coil Facility. Similar test set-up for RW B.
An analytical calculation of the exact magnetic flux density at any point in-between the Helmholtz coils is mathematically complex and involves the solution of some Bessel functions. In order to confirm that the experimental tests with a nearly uniform magnetic field can be compared with the numerical analysis which is assuming a perfectly uniform magnetic field around the RW, the Helmholtz coils have been modelled and simulated in COMSOL Multiphysics. As shown in Figure 7 and 8, the magnetic field decays rapidly outside the Helmholtz coil pair. However, the field uniformity close to the centre suffices for a comparison with the computer simulations. The magnetic field $B$ at the central point between the coils can be approximated with:

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

where $R$ is the radius of Helmholtz coils as well as the distance between the two coils, $n$ the number of turns in each coil and $I$ the coil current. The perm/deperm Helmholtz coils of the MCF have $n = 164$, $R = 600$ mm and $I \leq 30.7$ A, generating up to $\approx 7.5$ mT in the centre of the test set-up.

![Image](image1.png)

Figure 7: MCF simulation results with $B \approx 7.5$ mT and dummy RW.

![Image](image2.png)

Figure 8: Simulated MCF field with perm/deperm coil pair for different currents.
3.1.2 External Source - Magnetic Torquer

For the experimental tests, the CryoSat flight spare MTQ has been positioned at four different locations relative to the RW as shown in Figure 10. Since the CryoSat MTQ creates a relatively low magnetic field compared to larger, more relevant MTQs, a pair of laboratory coils have been alternatively used to generate a stronger magnetic dipole moment as depicted in the lower picture of Figure 9. The two coils from Leybold Didactic with type no. 562 131 have 480 windings each and up to 10 A current capacity.

![Figure 9: Test set-up with MTQ and lab coils in proximity of RW B. Similar test set-up for RW A.](image)

![Figure 10: Four locations of the CryoSat MTQ relative to the RW.](image)

3.2 RW Performance without External Field

Both reaction wheel types used for this investigation needs a run-in of several hours in order to reach a stable and repeatable loss torque behaviour over the complete speed range. By the run-in process, the local temperature distribution is stabilised and the ball bearings are ‘preconditioned’, mainly in terms of an even distribution of the lubricating oil and wetting of all functional surfaces. Since RWs are not operated during the final stages of spacecraft preparation, ground transport/storage and launch, it is important to be aware of the need for an appropriate run-in and to know the typical time a wheel requires to attain nominal behaviour. The run-in time varies with the RW type and individual conditions, for instance the time a particular wheel has been inactive. Run-in plots for both RW types after several years of stand-still/storage are shown in Figure 11, where the estimated friction torque is marked in grey and the evolution of a moving average in red.

As shown in Table 1, the maximum reaction torque as specified by the supplier is ±75 mNm for RW A and ±215 mNm for RW B. The actual loss torque of RW B in steady-state condition, i.e. at a constant speed of 1800 rpm, has been approximately 12 mNm after 7.5 hours run-in. RW A has reached a constant loss torque of approximately 15 mNm after about 4 hours of operation at 6000 rpm, with minor excursions during the run-in process due to some transient friction effects.
The nominal loss torque characteristics as a function of speeds after run-in are shown in Figure 12. The average stabilised loss torque characteristic depends on the RW type and differs with each supplier. Additionally, it tends to vary among individual hardware models with some moderate dispersion. The characteristics of the two test wheels were empirically determined by running the RWA at different steady-state speeds while estimating the loss torque on the basis of the telemetry data created by the wheels.

In this frame, a Coulomb friction torque component is assumed to be mainly caused by friction in the ball bearings, with a magnitude independent of speed. However, a larger part of the total loss torque is caused by viscous losses due to oil lubrication of the bearings, furthermore by some non-mechanical sources such as motor losses or residual aerodynamic drag. RW B shows a significant drop of the viscous losses above 1000 rpm. This effect might be caused by inlet starvation in the context of forming a stable oil film in the ball bearings, however this is only speculated, and it will not be investigated further in the frame of this thesis. It should be highlighted that the two test RWs have different angular momentum capacity, speed range, and size, and therefore a direct comparison of test and simulation results needs to be done with caution. Any loss torque induced by external magnetic fields will appear as an additional component on top of the nominal loss torque characteristic.
3.3 Reaction Wheel in Homogeneous Magnetic Field

The maximum loss torque due to an external magnetic field is determined by the difference between the average loss torque when the maximum flux density has been applied and the average loss torque before starting the magnetic field excitation profile. The temporal profiles of magnetic field excitation were generated using a waveform generator, which followed a Gaussian-like function as shown in Figure 13. The total duration of the waveform was two minutes, with one minute dwell time at maximum field intensity for each profile.

![Figure 13: Measured loss torque with $B = 5 \text{ mT}$ orthogonal to the RW A spin axis at 6000 rpm.](image)

3.3.1 Magnetic Field Parallel to Reaction Wheel Spin Axis

The experimentally determined loss torque due to a homogeneous external magnetic field parallel to the RW spin axis is shown in Figure 14 for both wheels. The resulting loss torque appears fairly independent of wheel speed and magnetic flux density. Hence, the results of the numerical simulations suggesting a negligible effect of a magnetic field applied parallel to the spin axis have been clearly confirmed.

![Figure 14: Experimental loss torque results due to a magnetic field parallel to the RW spin axis. Results (b) were obtained from an earlier test campaign in 2018.](image)

<table>
<thead>
<tr>
<th>Speed [rpm]</th>
<th>Applied Field [mT]</th>
<th>Loss Torque [mNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>1.0</td>
<td>-0.54</td>
</tr>
<tr>
<td>1800</td>
<td>3.0</td>
<td>-0.59 / 0.03</td>
</tr>
<tr>
<td>2700</td>
<td>5.0</td>
<td>-0.42</td>
</tr>
<tr>
<td>2700</td>
<td>7.5</td>
<td>-0.40</td>
</tr>
</tbody>
</table>
3.3.2 Magnetic Field Orthogonal to Reaction Wheel Spin Axis

The results of the more extensively conducted tests with the magnetic field being orthogonal to the RW spin axis are shown in Figure 15. In the plots, the discrete points represent the experimentally acquired data, while the solid and dotted lines show curve fitting results. The loss torque as a function of magnetic flux density for a RW with steel and aluminium rotor can be respectively approximated with:

\[
\tau_{\text{Loss,Steel}}(B) \propto B^3 \quad \tau_{\text{Loss,Aluminium}}(B) \propto B^2
\]

The loss torque \(\tau_{\text{Loss}}\) as a function of angular speed \(\omega\) for the aluminium rotor can be approximated with the empirically determined exponential model, which was previously used for eddy current brakes [5]:

\[
\tau_{\text{Loss,Aluminium}}(\omega) = \gamma \left( e^{-\beta \omega} - e^{-\alpha \omega} \right)
\]

The empirical parameters \(\alpha, \beta\) and \(\gamma\) are dependent on the flywheel design, such as rotor material, and the applied magnetic flux density \(B\). However, for the steel rotor the loss torque evolution as a function of wheel speed cannot be adequately approximated by the same empirical model, and the curves have been defined by spline interpolation.

![Figure 15: Experimental loss torque results due to an external magnetic field orthogonal to the RW spin axis. Results (b) are from a previous test campaign performed at ESA/ESTEC in 2018.](image-url)
3.4 Reaction Wheel with Magnetic Torquer (Inhomogeneous Field)

The experimental test results obtained with the reaction wheels close to the CryoSat magnetic torquer are presented in this section. The maximum loss torque due to the magnetic field created by a MTQ is determined by the difference between the average loss torque during the period of maximum field intensity and the average loss torque during a few seconds before powering the MTQ, as shown in Figure 16.

![Figure 16: Loss torque of RW B with 160 mA in both coils of MTQ at location 1 at 2700 rpm.](image)

3.4.1 Effect of Magnetic Torquer Orientation

For simplicity, only the nominal maximum current of 120 mA has been applied to both coils of the CryoSat MTQ. It has been placed directly adjacent to the test RW, as described in Figure 10, thus placing the wheel in the region of maximum external magnetic flux density.

As it can be seen in Figure 17, the three locations 1, 2 and 4 where the MTQ is closest to the outer rim of the flywheel causes the strongest effect on the RW loss torque. In addition, it must be highlighted that the wheel experiences higher loss torque when the MTQ is pointing in the radial direction regarding the RW spin axis. However, contrary to the findings when a homogeneous external magnetic field was applied, the parallel orientation of the MTQ has caused relatively high loss torque levels as well. The loss torque $\tau_{\text{Loss}}$ as a function of angular speed $\omega$ for the aluminium rotor can be approximated with the same empirically determined exponential model as used when an homogeneous magnetic field is acting, as previously described in Equation 6. Similarly as for the case of an homogeneous magnetic field, for the steel rotor the evolution of loss torque as function of speed cannot be adequately approximated and the curves have been defined by spline interpolation.

![Figure 17: Loss torque as function of wheel speed at different MTQ locations relative to RW. MTQ with 120 mA current in both coils generating approximately 40 mT at poles.](image)
3.4.2 Effect of Magnetic Torquer Distance

In this section, the impact of the distance between MTQ and RW is analysed. In order to verify the loss torque evolution with increasing magnetic dipole moment and flux density, two laboratory coils have been placed at location 1 directly adjacent to the RW such that the coils and the RW are in physical contact, with varying excitation currents. As depicted in Figure 18, the loss torque rapidly increases with higher magnetic flux density $B$ at the RW housing:

$$\tau_{\text{Loss,Steel}}(B) \propto B^2 \quad \tau_{\text{Loss,Aluminium}}(B) \propto B^2$$  \hspace{1cm} (7)

Moreover, the loss torque rapidly decreases over distance as the magnetic field decreases with approximately $1/d^{2.5}$ with $d$ being smaller than 2.5 m, and $1/d^3$ for $d$ being bigger than 2.5 m as will be shown later in section 4.1.2. Hence, the loss torque as function of distance $d$ for steel and aluminium rotors can be consequently approximated by combining Equation 7 with 10:

$$\tau_{\text{Loss}}(d)_{0.5-2.5m} \propto \left(\frac{1}{d^{2.5}}\right)^2 = \frac{1}{d^5} \quad \tau_{\text{Loss}}(d)_{>0.25m} \propto \left(\frac{1}{d^3}\right)^2 = \frac{1}{d^6}$$  \hspace{1cm} (8)

Figure 18: Two laboratory coils representing a large MTQ with varying excitation currents up to 10 A generating up to 65 mT at the poles.
4 Modelling and Simulation

In order to understand the physical phenomena of the results obtained with the experimental tests described in chapter 3, numerical analysis have been conducted with similar boundary conditions. For the simulation of the electromagnetic influence on the reaction wheel loss torque, the commercial Finite Element Analysis (FEA) software COMSOL Multiphysics has been utilised, featuring the well suited analysis modules Rotating Machinery, Magnetic and Magnetic and Electric Fields. All electromagnetic FEA carried out during this investigation have been treated as stationary or transient problems, using 3D models. The simulation models have very high numbers of Degrees of Freedom (DoFs) which requires high computational time, e.g. 18 hours for simulations with a duration of 0.05s. Therefore, only selected scenarios have been simulated. This chapter contains a brief overview on the governing equations forming the basis for the FEA and the interpretation of the results. It also discusses model creation in the software tool and the qualitative and quantitative results that were obtained.

4.1 Finite Element Analysis Model

The electromagnetic interactions have been analysed using the Finite Element Method (FEM) in order to solve the associated electromagnetic field problems numerically. As the first step, the two reaction wheels and a parametric model of a magnetic torquer have been modelled in a stand-alone environment in order to allow for modular simulations. At a later stage, each RW has been joined with the MTQ in a combined model file, furthermore with an external magnetic field in another file. Hence, four different model combinations as described in section 2.3 have been analysed and are outlined in the following sections.

4.1.1 Modelling of the Reaction Wheels

The modelling approach regarding the RWs for the numerical simulations is shown in Figure 19 and 20. At the start, simplified CAD assemblies of the two RWs have been created based on the information available, utilising the 3D CAD programme SolidWorks. Since the electromagnetic effects are expected to be caused by dynamic physical principles in the rotating parts, only the flywheel rotor including the motor magnets has been modelled.

In the area of Computer Aided Engineering (CAE), numerical simulations should be initiated and pursued with models as simple as possible in order to reduce the risk of modelling flaws and to keep the computation time down. Therefore, in a first step a 2D model of the rotor has been generated with COMSOL Multiphysics. In this way, the necessary modelling accuracy, mesh sensitivity and torque calculation methods for the 3D model can be determined. For validation, the results of different methods for torque calculation have been compared.

After thorough validation of the 2D model results, a more complex 3D model has been created. Within this step, the CAD assembly has been imported into COMSOL Multiphysics where all properties and boundary conditions have been applied. In Figure 19b and 20b, the parts manufactured from steel are highlighted in dark grey, those made of aluminium in light grey, and the motor magnets are marked in blue and red, according to the direction of their alternating radial polarisation. The relevant material properties for both RW types are shown in Table 3. As next step, the mesh consisting of triangular elements has been defined. Since a higher resolution of the mesh causes increased computation time, a trade-off has to be made between accuracy of the solution and the time need to complete a simulation. The size and geometry of each boundary layer and part has been manually modelled to ensure sufficient detail and, thus, adequate results.
Table 3: Material properties used for the reaction wheel FEA models.

<table>
<thead>
<tr>
<th>Part</th>
<th>Relative Permeability</th>
<th>Electrical Conductivity [S/m]</th>
<th>Remnant Flux Density [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW A - Aluminium rotor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>1</td>
<td>3.66e7</td>
<td></td>
</tr>
<tr>
<td>Ball bearing unit</td>
<td>800</td>
<td>0.42e7</td>
<td></td>
</tr>
<tr>
<td>Magnets</td>
<td>1.0942</td>
<td>0.18e7</td>
<td>1</td>
</tr>
<tr>
<td>RW B - Steel rotor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer rim</td>
<td>400</td>
<td>0.14e7</td>
<td></td>
</tr>
<tr>
<td>Damping rings</td>
<td>1</td>
<td>3.77e7</td>
<td></td>
</tr>
<tr>
<td>Ball bearing unit</td>
<td>800</td>
<td>0.42e7</td>
<td></td>
</tr>
<tr>
<td>Magnets</td>
<td>1.0942</td>
<td>0.18e7</td>
<td>1</td>
</tr>
</tbody>
</table>

The environment surrounding the RW is modelled as shown in Figure 21. The geometry is split into several domains, where every enclosed area represents a separate domain. In Figure 21a, the rotating domain is marked in blue. As it can be seen, the rotating domain and the boundaries between the different domains require a fine mesh, which increases the computation time considerably. The static magnetic field generated by the permanent magnets of the motor is shown in Figure 21b.
4. Modelling & Simulation

4.1.2 Modelling of the Magnetic Torquer

The simplified model of the MTQ has been directly created in COMSOL Multiphysics. It consists of two long coils, being primary and redundant, around a high-permeability core. The resulting magnetic flux density is shown in Figure 22a. The design parameters are defined as variables, thus allowing ‘parametric sweeps’ in order to analyse different MTQs and the impact of their respective magnetic dipole on RW performance. The Fe-Ni core features a non-linear B-H characteristic, which strongly contributes to the magnetic dipole generated by the CryoSat MTQ as shown in Figure 22b.

\[
m = \iiint_V M \, dV
\]  

(9)

In order to confirm the correct modelling in COMSOL Multiphysics, the dipole moment \( m \) has been computed and compared with the specification and test data obtained with the flight hardware.
As shown in Table 4, the specified magnetic dipole moment \( m \) and that computed \( m_{\text{COMSOL}} \) with only the primary coil being active have a difference of 1\%., thus proving sufficient modelling accuracy. By applying a current on the secondary, redundant coil in addition, the dipole moment can be increased to 47.9 Am\(^2\).

<table>
<thead>
<tr>
<th>Applied coils</th>
<th>Applied current [mA]</th>
<th>( m ) [Am(^2)]</th>
<th>( m_{\text{COMSOL}} ) [Am(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>30</td>
<td>29.5</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>-</td>
<td>43.6</td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>39</td>
<td>36.7</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>-</td>
<td>47.9</td>
</tr>
</tbody>
</table>

![Figure 23: Magnetic flux density along the central axis of the CryoSat MTQ.](image)

The magnetic flux density as a function of distance \( d \) from the MTQs poles is shown in Figure 24. It is mainly a function of coil current, coil geometry such as cylindrical shape, radius, length, etc., and the magnetic permeability of the core material. The magnetic flux density \( B \) caused by a perfect magnetic dipole decays with \( 1/d^3 \) where \( d \) is the far-field distance from the dipole [1]. A far-field condition can be assumed if the length \( l \) of the MTQ \( \ll \) distance \( d \). In a spacecraft configuration, the distance between MTQ and RW can vary between approximately 0.5 m and 5 m. The simulations conducted with COMSOL Multiphysics may be summarised as in Equation 10 and therefore suggest that a field decay with \( 1/d^3 \) can be assumed when \( d > 13 \cdot l \).

\[
B_{MTQ}(d)_{0.5–2.5m} \propto \frac{1}{d^{2.5}} \quad B_{MTQ}(d)_{>2.5m} \propto \frac{1}{d^3}
\]  

(10)

![Figure 24: Axial far-field decay of the CryoSat MTQ magnetic dipole field. MTQ with 120 mA current applied on both coils with distance starting at the poles of the MTQ.](image)
4.2 Computational Methods

A key aspect when modelling rotating machinery via FEA concerns the numerical computation of the forces and torques acting on ferromagnetic bodies in nonlinear magnetic fields. In COMSOL Multiphysics, the most common techniques to evaluate these quantities are Maxwell Stress Tensor, Virtual Work or Eggshell Method. When magnetic fields have low magnitudes as considered in this thesis, all of the aforementioned techniques provide sufficient accuracy [6]. However, they all have some advantages and disadvantages. The more general Maxwell Stress Tensor method is highly mesh dependent, as the solution’s accuracy increases with higher numbers of elements. In order to avoid effects of mesh sensitivity, the eggshell approach has been preferred from the other two methods as it has been proven to be more accurate [7]. The eggshell method allows computation of the total torque by integrating the magnetic stress tensor $T_{ms}$ over an arbitrary shell $V$ surrounding the body of interest with the general equation being:

$$
\tau_{\text{eggshell}} = \int_V r \times (T_{ms} \nabla u) dV
$$

where $u$ is calculated by Poisson’s equation on the shell, with $u = 0$ on the inside boundary and $u = 1$ on the outside boundary, as illustrated in Figure 25b. For the 3D simulations, the mesh in the defined eggshell area has to be extremely fine as shown in Figure 25a.

![Highlighted meshed shell.](image)

![Dependent variable $u$.](image)

Figure 25: Modelled area for eggshell method based torque calculations.

4.3 Reaction Wheel in Homogeneous Magnetic Field

The simulated loss torque due to an external magnetic field has been determined with the eggshell approach. The magnetic field interacting with the rotating domain needs a certain amount of time to reach stationary behaviour at a predefined constant speed because the initial conditions are not known beforehand. Therefore, the time-dependency of the simulation results needs to be respected.

4.3.1 Magnetic Field Parallel to Reaction Wheel Spin Axis

The numerical simulations with both reaction wheels show negligible effect on loss torque when the rotation axis is parallel to the external magnetic field, as illustrated in Figure 26. Moreover, the extremely small loss torque is independent of wheel speed. The current density is homogeneous over the flywheel circumference and generates eddy current loops over the entire rotor, as it can be noticed by the arrows in Figure 26b.
4.3.2 Magnetic Field Orthogonal to Reaction Wheel Spin Axis

The numerical simulation of the RWs in an external homogeneous magnetic field orthogonal to the RW spin axis yields the results shown in Figure 28a and 28b. It can be seen that the maximum current density for ferromagnetic materials, such as many steel grades, is in the regions of ±x-direction. For the aluminium rotor, the current density peaks at a 30° angle to the ±y-direction. Further analyses including a separation of the aluminium rotor from the steel Ball Bearing Unit (BBU) show that the maximum current density will be in ±y-direction as shown in Figure 28c. Moreover, it can be seen that ferromagnetic material such as the steel grade of the outer rim and the BBU for both RW types gives rise to strong distortion and ‘guidance’ of the local magnetic field. In this context, ferromagnetic parts will also provide magnetic shielding, for example on the damping rings and the inner region of the flywheel rotor.

It has to be noted that the numerical solution regarding the loss torque is time-dependent. When the external magnetic field is activated, it takes typically less than one second to stabilise and to get steady-state eddy currents. Hence, in the following only the last computed value of the loss torque’s temporal evolution has been taken into consideration for the analysis. The simulated results of the loss torque as a function of wheel speed and magnetic field are shown in Figure 27.
(a) RW A - aluminium rotor.

(b) RW B - steel rotor.

(c) Geometry of the RW B with aluminium rotor.

Figure 28: RWs rotating at 2000 rpm in 5 mT external magnetic field. Left figures: Magnetic flux density. Black lines represent magnetic iso-flux lines and direction. Right figures: Current density magnitude and direction.
4.4 Reaction Wheel with Magnetic Torquer (Inhomogeneous Field)

The numerical simulation results for the reaction wheels in proximity of the CryoSat MTQ are discussed in this section. Similar to the simulations performed with an homogeneous external magnetic field, the results are time-dependent with an initial transient followed by stationary stabilisation, and all analysis problems are modelled in 3D. The numerical simulations with applied current to the primary coil of the MTQ, being orthogonal (location 1) and parallel (location 3) to the RW’s spin axis are shown in Figure 30. The simulated results of the loss torque with varying distance \(d\) of the MTQ with both coils excited at location 1 and 3 are illustrated in Figure 29. The MTQ with 1 A current applied on one coil generates 140 mT at the axial end face of the MTQ, while 1 A in both coils results in 220 mT at the axial end face. At a distance of 0.5 m, this only causes 0.05 mT and 0.075 mT respectively at the rim of the RW. No major influence of the choice of flywheel material on the loss torque can be observed.

![Figure 29](image_url)

(a) Location 3, 1000 rpm  
(b) Location 1, 6000 rpm  

Figure 29: Loss torque with 1 A applied current to MTQ as function of distance.

![Figure 30](image_url)

(a) RW A.  
(b) RW A.  
(c) RW B.  
(d) RW B.  

Figure 30: Current density magnitude and direction for RW rotating at 1000 rpm. MTQ with 1 A current in one coil at 7 cm distance. (a) and (c) at location 1. (b) and (d) at location 3.
5 Detection of Reaction Wheel Spin Direction

During the experiments conducted with different reaction wheels, variations in the magnetic field generated by the wheels themselves depending on flywheel rotor position have been observed. Effectively, a magnetic dipole has been identified that is caused by the permanent magnets of the RW motor sub-assembly. Naturally, the individual permanent magnets as used in electric motors have some dispersion due to manufacturing tolerances, which results in some variability of their remanent flux density. Typically, the remanence may vary within ±3% [8]. Assuming that the remanence of the 16 permanent magnets in the motors of the test RWs will always have some random and asymmetric distribution, the rotating part of the motor will appear as rotating magnetic multipole and can be eventually reduced and simplified to a magnetic dipole beyond a certain distance. In the laboratory experiments performed, a ‘reduction’ to a rotating magnetic dipole has been observed starting at a distance as close as 5 mm from the spinning rotor.

This section briefly describes the development of a technique used to independently detect the sense of rotation i.e. clockwise or anti-clockwise for a RW after mounting on a spacecraft without using the internal tachometer sensor and the resulting telemetry signal generated by the wheel. Previously, an in-flight anomaly due to wrong polarity of the RW control and, thus, a spin direction opposite to that expected, has been encountered on an ESA spacecraft. Therefore, an independent check before launch has been requested for new missions. An established method to identify the spin direction is based on the measurement of interface forces using a multi-component dynamometric measurement platform. However, that option cannot be applied once a RW is mounted on a spacecraft. Hence, there is a need for a simple, quick and independent method which is non-intrusive and preferably contactless to determine the spin direction of wheels at spacecraft level. In this chapter, a method is presented, which uses the rotating magnetic field created by the RW motor to determine the sense of rotation.

As the motor magnets and thus the magnetic dipole will rotate with the RW, a locally fixed and non-moving magnetometer will pick up the change in the magnetic field. By analysing the phase relationship between the magnetic field by measuring the magnitude of the flux density in x- and y-directions, the spin direction of the RW can be reliably determined. In the frame of the investigations at ESA/ESTEC, a smartphone app has been developed based on the Python programming language, which utilises the built-in triaxial magnetic field sensor to determine the rotation sense of RWs nearly in real time. The following steps are being performed within the programmed app:

1. The two time-domain signals of the changing magnetic field in x- and y-directions are acquired and normalised as shown in the upper picture of Figure 31b.

2. Both signals are combined into a complex number vector with x being the real part and y comprising the imaginary part.

3. A Fast Fourier Transform (FFT) and shift operation (fftshift) is applied on the complex number vector.

4. Depending on the position of the highest peak, which is corresponding with the rotation frequency of the wheel, being either on the negative or positive side of the spectrum, the spin direction can be determined as shown in the lower picture of Figure 31b.
As the magnetic field signal deteriorates over distance by a factor of $1/d^3$, the quality of the detected signal gets significantly worse in terms of the signal-to-noise ratio. Therefore, the smartphone app also gives an indication on the confidence as regards the measurement. For this purpose, the two highest peaks are divided by each other. The smartphone app has been verified on the Herschel and Artemis flight spare RWs. The upper half of the housing had been removed from the latter, as shown in Figure 31c.

Figure 31: Smartphone app for the detection of RW spin direction.

This app works as a "proof of concept", to show how the magnetic field from the RW, with relative simple sensors and maths can be used to easily detect speed and spin direction of RWs. In the framework of this thesis, it is a result of the natural engineering curiosity and development that appears from analysing measurement data, and then utilising that curiosity in a different context than originally intended.
6 Discussion

In this chapter, the results of the numerical simulation and the experiments are compared. Moreover, several aspects are highlighted, which might have contributed to systematic and random errors in the simulation output as well as in the test data.

6.1 Error Sources

Before comparing the simulation and experimental results, the main potential sources of error have to be identified and assessed:

1. The two test reaction wheels have different sizes (diameter: 308 mm and 347 mm). Therefore, care has to be taken when comparing the absolute values of both wheels such as loss torque.

2. The representation of the flywheel rotors in the FEA models has been simplified and excludes a number of relevant parts and connecting interfaces such as the five spokes of the steel flywheel.

3. Some material properties were not known with sufficient accuracy and confidence, such as the ferromagnetic properties of the steels used should be described by a nonlinear B-H curve rather than a constant estimate of relative permeability $\mu_r$ as assumed for this investigation. Furthermore, the electrical conductivity has a strong impact on the magnitudes of eddy current. However, it is not exactly known for the metal alloys used.

4. Ferromagnetic materials cause hysteresis losses, particularly when exposed to alternating magnetic fields, which have not been taken into account in the FEA model.

5. The experimental tests were conducted using a relatively small magnetic torquer and laboratory coils, causing sometimes a relatively low signal-to-noise ratio.

6.2 Correlation of Simulation Results and Test Data

It has to be highlighted that the material properties have a strong influence on the numerical simulation results, especially electrical conductivity and magnetic permeability. Generally, if ferromagnetic materials are used for the flywheel rotor, the influence on the loss torque is bigger than with paramagnetic materials such as aluminium, which hardly interfere with magnetic fields.

6.2.1 Findings regarding Physical Phenomena

The observed physical phenomena and in particular those leading to eddy currents can be described on the basis of Lorentz forces acting on charged particles. For paramagnetic materials such as aluminium, the direction of the resulting Lorentz forces tends to be more evident than for ferromagnetic materials, because the external field remains virtually undisturbed. Free electrons in the bulk metal structure will be displaced by the Lorentz forces $\vec{F}_L$ in accordance with the cross product of the local velocity vector $\vec{v}$ of the moving metallic body and the magnetic flux density vector $\vec{B}$ in the environment:

$$\vec{F}_L = \vec{v} \times \vec{B}$$  \hspace{1cm} (12)

Lorentz forces occur orthogonal to both, the velocity and magnetic flux vectors. This explains the negligible effect of an external homogeneous magnetic field parallel to the RW spin axis, because the dominating part of the Lorentz forces will point in radial direction of the reaction wheel. The effect of Lorentz forces can be noticed in Figure 32, where the electron concentration is in $\pm x$-direction near the outer rim. In this conjunction, the closed loops or the curls in the vector field represent the
eddy currents, which are genuinely caused by the locally changing magnetic field and the electron flow in the direction of equalising the induced electrical potential. In the flywheel cases specifically studied here, eddy currents tend to be stronger in ferromagnetic materials as seen in Figure 33b with a steel rotor, than in paramagnetic materials as seen in Figure 32b with an aluminium rotor, since ferromagnetism gives rise to significant distortion and guidance of the magnetic field. This effect appears to overcompensate for the lower electrical conductivity of steels compared to aluminium.

![Figure 32: Physical phenomena explanation for an aluminium flywheel rotor.](image)

Furthermore, it can be seen that a steel flywheel rotor rim has a peak current density in $\pm x$-direction, while an aluminium flywheel rotor rim shows the peak in $\pm y$-direction. When the aluminium rotor is combined with the BBU, the resulting peak of current density will be rotated by some angle in-between the $x$- and $y$-directions. In general, all metallic parts forming the flywheel rotor have to be carefully considered as they all might be susceptible for the flow of eddy currents.

In conclusion, eddy currents $I_{Eddy}$ can be observed in both wheel types, as shown in Figure 34. However, the steel flywheel rim gives rise to effects significantly amplifying local eddy currents causing a much higher loss torque compared to the aluminium flywheel.

![Figure 33: Physical phenomena explanation for a steel flywheel rotor.](image)
6.2.2 Quantitative Assessment of Influence Factors

In this section, the results of the experimental tests are compared with those of the numerical analysis, mainly regarding the specific magnitudes obtained as well as the impact of operational and design parameters. The established relations between RW loss torque $\tau_{\text{Loss}}$, magnetic flux density $B$, wheel speed $\omega$ and distance $d$ are shown in Table 5 for the experimental tests as well as the numerical simulations. Generally, the loss torque increases with wheel speed and external magnetic field. In Table 5, only the homogeneous external magnetic field orthogonal to the wheels spin axis has been taken into account, furthermore location 1 (side, middle) of the MTQ relative to the RWs. A magnetic field parallel to the wheel spin axes as well as the MTQ in location 3 (centre, front) showed negligible effect on the loss torque. Comparing the obtained relations for the experimental tests and numerical investigations proofs that the numerical simulation is well suited for analysis with aluminium flywheel rotors, but still needs improvements to model the steel flywheel rotors.

### Table 5: Comparison of trends obtained from experimental and simulation results.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Experimental $\tau_{\text{Loss}}$</th>
<th>Simulated $\tau_{\text{Loss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Homogeneous Magnetic Field</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Flux Density</td>
<td>$\tau_{\text{Loss,Steel}}(B)$</td>
<td>$\propto B^3$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{Loss,Alu}}(B)$</td>
<td>$\propto B^2$</td>
</tr>
<tr>
<td>Wheel Speed</td>
<td>$\tau_{\text{Loss,Steel}}(\omega)$</td>
<td>$\gamma (e^{-\beta \omega} - e^{-\alpha \omega})$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{Loss,Alu}}(\omega)$</td>
<td></td>
</tr>
<tr>
<td><strong>Inhomogeneous Magnetic Field (Location 1 of MTQ)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Flux Density</td>
<td>$\tau_{\text{Loss,Steel}}(B)$</td>
<td>$\propto B^2$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{Loss,Alu}}(B)$</td>
<td>$\propto B^2$</td>
</tr>
<tr>
<td>Wheel Speed</td>
<td>$\tau_{\text{Loss,Steel}}(\omega)$</td>
<td>$\gamma (e^{-\beta \omega} - e^{-\alpha \omega})$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{Loss,Alu}}(\omega)$</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>$\tau_{\text{Loss,Steel}}(d)$</td>
<td>$\propto 1/d^5 / \propto 1/d^6$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{Loss,Alu}}(d)$</td>
<td>$\propto 1/d^5 / \propto 1/d^6$</td>
</tr>
</tbody>
</table>
The absolute error between the numerical investigations and experimental tests for the different scenarios are shown in Figure 35 for $B = 5 \text{ mT}$ and $\omega = 2000 \text{ rpm}$. The numerical simulation results in approx. 10% error for the aluminium rotor RW A, while having a very high difference in magnitude for the steel rotor RW B. This is most likely due to the points highlighted in subsection 6.1, such as the missing contribution by the five spokes in the RW B FEA model. However, the simulation runs did not converge when the spokes and more complex material properties, such as nonlinear B-H curves, were included in the model and thus, presumably require much more computing power.

![Figure 35: Absolute error comparison for homogeneous magnetic fields. Dashed line and discrete points indicate simulation data; solid lines indicate experimental data.](image)

6.2.3 Case Study

In an independent assessment performed for an ongoing ESA project, the RW loss torque due to an external magnetic field of 1 mT at the outer rim was estimated to be approximately 13 mNm. However, it was assumed that the loss torque changes in a roughly linear fashion with the magnetic field $\tau_{\text{Loss}} \propto B$, as described in subsection 2.3. Taking the findings in this thesis concerning the relationships in Table 5 into account, this assumption should be revisited.

For the ESA mission concerned, the initial assumptions along with COMSOL simulation results are shown in Figure 36. It can be seen that the magnetic torquer will have a different effect depending on whether the flywheel material is paramagnetic or ferromagnetic. In this context, it can be inferred that the flywheel material choice is negligible when using small MTQs such as 30 Am², while the material choice has a rather big impact with large MTQs such as 400 Am². In that case, a steel flywheel rotor will cause a significantly higher loss torque than an aluminium flywheel rotor. However, it should also be noted that the initial assumption of 29 mNm loss torque for 3 mT scaling down to 13 mNm at 1 mT appears simplifying too much. Therefore, when extrapolating for higher magnetic flux densities, the additional loss torque might be severely underestimated.
6. Discussion

(a) Magnetic flux density.

(b) Loss torque as a function of magnetic flux density at RW. Initially the relation was assumed to be linear. However, numerical investigations have proven that a power function is more accurate.

(c) Current density.

Figure 36: Case Study - Loss torque effect with large MTQ. Initially the relation was assumed to be linear. However, numerical investigations have proven that a power function is more accurate.
Conclusions and Outlook

The findings within this investigation are summarised within this chapter while answering the initial problem statement:

*How and with what severity do external magnetic fields affect reaction wheel performance, and how can this be proven using laboratory tests and computer-based analysis?*

When external homogeneous magnetic fields are acting upon reaction wheels, only magnetic fields orthogonal to the spin axis cause a significantly increased loss torque. Generally, the loss torque increases with higher wheel speed and external magnetic flux density. Furthermore, the loss torque strongly increases when the flywheel rotor is made of ferromagnetic material, i.e. with a scale factor of approximately $B^3$ compared to paramagnetic material where the scale factor is around $B^2$.

When inhomogeneous magnetic fields such as generated by magnetic torquers are present close to reaction wheels, the most pronounced loss torque increase occurs when the magnetic torquer is pointing towards the outer rim of the flywheel. Similar to the observations with homogeneous magnetic fields, an increase of wheel speed or magnetic flux density causes a higher loss torque. In this context, the material choice for the flywheel does not play an important role when the magnetic torquer is in the range of $30 \text{ Am}^2$, while large magnetic torquers in the range of $400 \text{ Am}^2$ tend to elevate the loss torque much more for ferromagnetic materials than paramagnetic materials. Furthermore, the loss torque due external magnetic fields rapidly diminishes with approximately $\tau_{\text{Loss}} \propto 1/d^6$ when the distance between magnetic torquers and reaction wheels gets larger. This is due to the magnetic field generated by the magnetic torquer reducing over distance with $B \propto 1/d^3$ for far-field considerations. Some recommended potential measures and options to reduce the impact of magnetic torquers on reaction wheel loss torque include:

- Maximise the distance between both actuator types. A minimum recommendable distance mainly depends on the magnetic torquer used and their maximum magnetic dipole moment.
- Use a magnetically shielding material for the reaction wheel housing or in combination with the housing.
- Utilisation of aluminium instead of ferromagnetic steel for the flywheel.
- Reduction of eddy current flow paths in the flywheel parts by electrical insulation.

Above-listed options are particularly interesting when strong magnetic torquers are used, especially on large LEO satellites in polar orbits. Finally, it should be emphasised that modelling and simulation in the domain of transient electromagnetic problems and rotating items, often necessitating 3D models due to the underlying physics, is very demanding and requires substantial computational effort and time. For instance, a single simulation run might take 18 hours for a simulated time of 50 ms. When materials with high magnetic permeability are involved, the boundary mesh and solver settings have to be adjusted carefully in order to achieve convergence, which results in very high number of DoFs in the FEA. This also applies to materials with high electrical conductivity, however with less impact on the numerical solver. Potential future work in this area might include:

- Further refinement and completion of the COMSOL Multiphysics models, for instance the BBU, the flywheel spokes, the housing, verified B-H curves for the ferromagnetic steel grades.
- Experimental tests and numerical analysis with stronger magnetic torquers or alternatively using laboratory coils, which generate a magnetic dipole moment much higher than that of the CryoSat magnetic torquer utilised within this thesis.

Thereby the problem statement is considered fully answered.
Bibliography


