Eddy Current Effects in Spacecraft Mechanisms

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Abstract

The mastering of electromagnetic design features in spacecraft mechanisms, including desired or undesired effects due to eddy currents, has become a promising area for a model-based design and development approach. In this frame, multiphysics type investigations have been performed on a simplified experimental test set-up and on flight representative reaction wheel assemblies. The test results have been successfully correlated with simulation output obtained from basic linearized models up to transient nonlinear representations of eddy current effects in complex geometries. The impact of critical parameters like the electrical conductivity of materials as a function of temperature has been particularly studied.

Introduction and Motivation

Many actuators used in spacecraft applications are based on electromagnetic principles for their function and operation. In this overall context, eddy currents in electromagnetic devices may have a desired effect, for instance when creating a resistive torque in speed regulators (or dampers) as used for controlling the deployment of solar arrays or other spacecraft appendages. In many other cases (e.g. reaction wheel assemblies involving electric motors), eddy currents are associated with losses and/or motion resistance, which are normally undesired and to be minimized [1]. However, in comparison to other industrial sectors, space mechanisms are often used for very specialized and one-of-a-kind tasks, relying on very few hardware prototypes and limited testing in the course of their development. Therefore, the understanding & optimization of electromagnetic design features in their interaction with other physical effects has become a very important objective, which has been the main motivation for the research presented in this paper.

Theoretical Framework

Eddy currents have been subject of theoretical elaborations and experiments since the 19th century when Michael Faraday and Léon Foucault were working on this topic. They may be regarded as loops of electric current induced within conductive materials by a varying external magnetic field. When considering a disk rotating in an air gap between the pole pieces of a magnet, the resulting torque grows with the angular speed of the disk, which may be approximated by Eq. 1 within a limited speed range [2]:

$$T = \frac{\pi\, b\, c^2 a^2}{2} \cdot \left(1 - \frac{r^2\, a^2}{(r^2 - c^2)}\right) \cdot \sigma\, B^2\, \omega \qquad \textit{(Eq. 1)}$$

T	…	resistive torque due to eddy currents	[Nm]
ω	…	angular speed of the disk	[rad/s]
σ	…	electrical (bulk) conductivity of the disk material	[S/m]
B	…	magnetic flux density (average) in the air gap	[T]
a, b, c, r	…	geometric parameters	[m]

In fact, the resistive torque has been shown to grow linearly (according to Eq. 1) at low speeds only, levelling before reaching a maximum at medium speeds and finally decreasing at higher speeds [2].

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When eddy currents flow in a spinning metallic disk, they generate their own magnetic field that counteracts the external (source) magnetic field. At sufficiently high speeds, the resulting total magnetic field significantly reduces, and, hence, the eddy current related torque stays well below the linear growth observed at low speeds [3].

Furthermore, a basic model according to Eq. 1 may assume the disk material to feature a constant electrical conductivity. However, as the temperature rises due to Joule heating, the disk's electrical conductivity decreases (in an approximately linear fashion, acknowledging the temperature coefficient of resistance). For many metals, this coefficient exceeds 0.004/K, and therefore even small temperature changes considerably reduce the electrical conductivity. Joule heating reduces the eddy currents in the spinning disk (by Ohm's law). The consequences are manifold: Lower eddy currents decrease the resulting Lorentz forces and thus the resistive torque. However, they also generate a lower counteracting magnetic field that causes the total magnetic field to be higher again. Hence, assuming constant speed, the spinning disk system will reach a steady-state equilibrium governed by Maxwell's equations together with the relevant thermodynamic and mechanical effects and boundary conditions. In the following paragraphs, the analytical and experimental study with focus on the evolution of the resistive torque vs. speed is outlined.

Modelling and Simulation of a Simplified Case

In the frame of the study, modelling and simulation has been performed using the software tools ANSYS Maxwell® and COMSOL Multiphysics®, with controlled modification of the parameters under investigation. The model geometry has matched the relevant parts of the eddy current test bench described in the following paragraph. The size of the air gap has been parameterized for easy adjustment of the geometry. Furthermore, the disk thickness has been varied. Figure 1 shows the meshed geometry in ANSYS Maxwell® including the materials used.

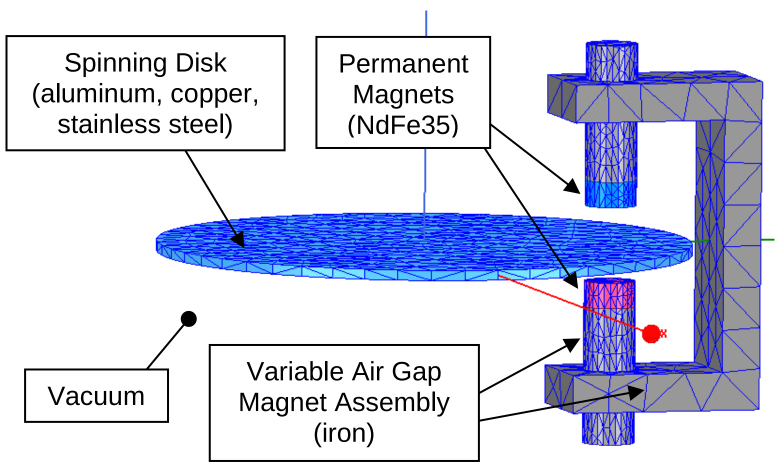


Figure 1 – Model configuration & mesh in ANSYS Maxwell®

Many transient (time-domain) simulation runs have been carried out to study the sensitivity to parameter changes (in particular, disk thickness, disk material & air gap dimension), across the full speed range (0…4000 rpm). The following model parameters have been used for the simulation runs:

- Air gap (i.e. distance between the permanent magnets): 20…80 mm (in 10 mm steps)
- Materials of the sample disks: aluminum, copper & stainless steel
- Thickness of the sample disks: 2 & 3 mm

Serving as an example, Figure 2 shows the simulation results in terms of resistive torque vs. disk speed. It represents a case with a 2-mm copper disk in a 40-mm air gap. As already indicated above, a linear trend is observed in the low speed range (here: below approx. 1000 rpm). At higher speeds and up to 3000 rpm, the torque increases with a lower gradient. After passing a maximum, the torque starts decreasing in the upper speed range. As suggested by theory, at high speeds the induced eddy currents give rise to a secondary magnetic field that opposes the primary one. Whilst at low speeds this effect remains small, the counteracting magnetic field becomes significant and eventually leads to a drop of the resistive torque. In order to confirm this effect, among others, a dedicated test bench was created.

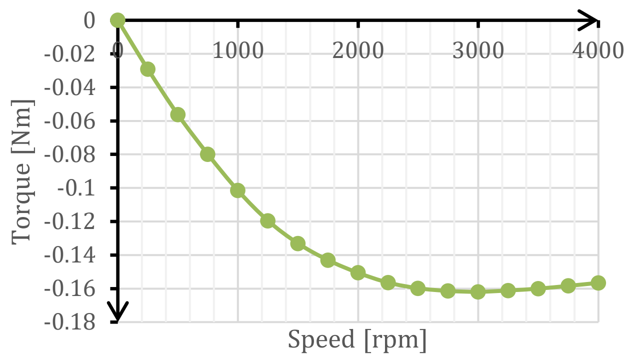


Figure 2 – Resistive torque vs. speed (simulation results for 2-mm copper disk, 40-mm air gap)

Eddy Current Test Bench

The experimental objectives of the Eddy Current Test Bench (ECTB) have been to measure the resistive torque and Joule heating (due to eddy current dissipation) as a function of the speed of the rotating disk (driven by a brushless DC motor). Measured values have been correlated with results obtained from two independent models of the test setup (in Maxwell and COMSOL), as well as a simplified analytical model. The ECTB has been designed such that the parameters of Equation 1 are easily tweaked (e.g., air gap size, disk thickness and disk material). When the influence of disk thickness was to be measured, individual disks of identical material and geometry (apart from thickness) have been compared. When the influence of disk material was to be measured, disks of identical geometry have been compared. A simplified geometry has facilitated the experiments as it has minimized the effect of unknown and unpredictable factors that would otherwise have influenced the test bench results.

The ECTB has been designed to provide a constant magnetic field using a variable air gap magnet. The main components of the ECTB (as shown in Figure 3) are:

- Rotating disk (of different materials and thicknesses)
- Motor drive assembly (brushless DC motor with casing, drive electronics and torque transducer)
- Variable air gap magnet assembly
- Translation stages (for the variable air gap magnet assembly), including baseplate

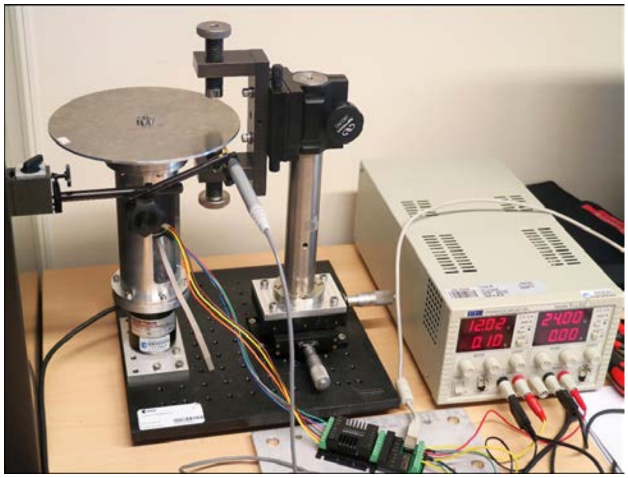


Figure 3 - ECTB experimental test setup

One of the key results of the investigation has been the measurement of the eddy current related torque (see Figure 4) over a speed range sufficiently wide to observe the predicted torque drop at high speeds. The orange curve represents directly measured resistive torque due to eddy currents (by subtracting the measured non-magnetic loss torque from the total measured torque). The curves obtained through the Maxwell and COMSOL models are shown in green and blue, respectively. As explained below, different conductivity values have also been introduced into the models.

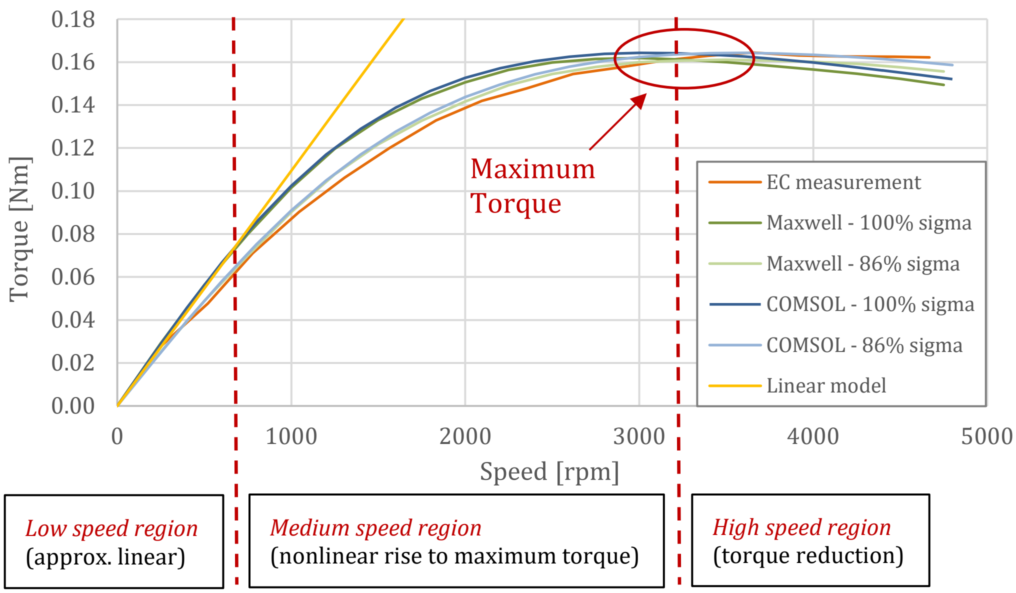
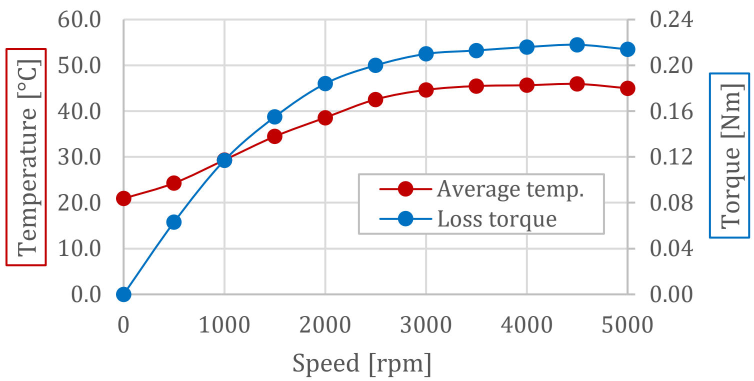


Figure 4 - Correlated results of eddy current related torque (2-mm copper disk, 40-mm air gap)

From a multiphysics point of view, the mechanical, electromagnetic as well as thermodynamic effects are strongly intertwined in the case studied. Joule heating (eddy currents dissipating in the disk) has been shown to directly depend on the torque.

Figure 5 (left side) presents data for a configuration of the ECTB for which the air gap has been minimized to 35 mm (reaching motor limits), in order to maximize the measured torque and Joule heating.



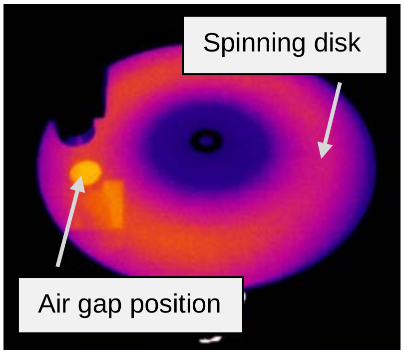


Figure 5 - Left: average temperature & torque vs. speed (2-mm copper disc, 35-mm air gap); Right: measured temperature distribution of spinning disk (same configuration as left, at 4500 rpm)

Temperature measurements have been made using infrared thermometers pointed at a high emissivity face of the spinning disk (ensured by coating it with matte black paint), and torque measurements have been conducted in parallel.

It is evident in Figure 5 (left side) that the rises in torque and temperature fall together, as predicted. Regarding the evolution of conductivity of the disk as function of temperature, the largest measured increase above room temperature has been approximately +35 K (= 55°C - 20°C).

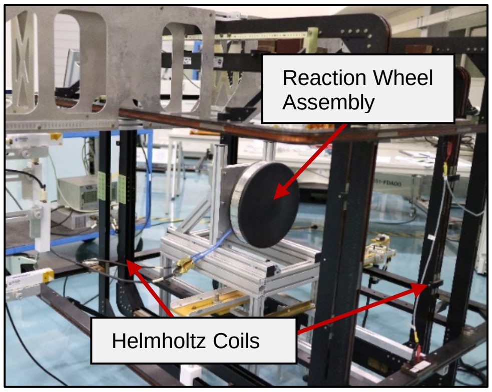
Figure 5 (right side) shows a thermal image of the ECTB running in this configuration of maximum heating. The annular shape of the temperature distribution corresponds to where most of the heating occurs, namely where the magnetic field has been strongest (directly between the magnet's pole pieces that can be seen left side of the image).

Assuming the temperature coefficient of resistance to be 0.00404/K for copper, this implies a decrease in conductivity of the spinning copper disk of more than 14% compared to its value at ambient temperature. The resulting Lorentz force (and so the torque) also drop by a corresponding amount. Thus, thermal effects are not negligible in this context. An adjusted conductivity has been used for the respective simulation runs in the Maxwell and COMSOL, shown in Figure 4 as the "86% sigma" curves (the original "100% sigma" curves are for a conductivity that is not adjusted). As can be seen, this has resulted in even closer correlation of the results with measurements.

Eddy Current Effects in Reaction Wheels

A relevant case where eddy currents are an unwanted side effect can be found in reaction wheels for spacecraft attitude control. They typically consist of an electric motor driving a metallic flywheel with speeds up to 6000 rpm and more. Under the presence of a relatively strong external magnetic field, possibly originating from magnetic torque rods used as secondary actuators, an additional loss torque due to eddy currents in the rotating flywheel may occur and result in degraded performance of the reaction wheel concerned.

In order to quantify this effect, a dedicated test was devised using the Magnetic Coil Facility at ESA/ESTEC, which features Helmholtz coils able to generate magnetic fields up to 7.5 mT. A reaction wheel was placed in the center of the Helmholtz coils and operated under varying magnetic flux densities. The reaction wheel assembly used comprises a spoked flywheel made from stainless steel. Its maximum motor torque is about 235 mNm, over a speed range up to 2700 rpm. The loss torque of the reaction wheel assembly is typically in the range of 10 to 15 mNm (excluding the effect of any ambient/external magnetic fields).



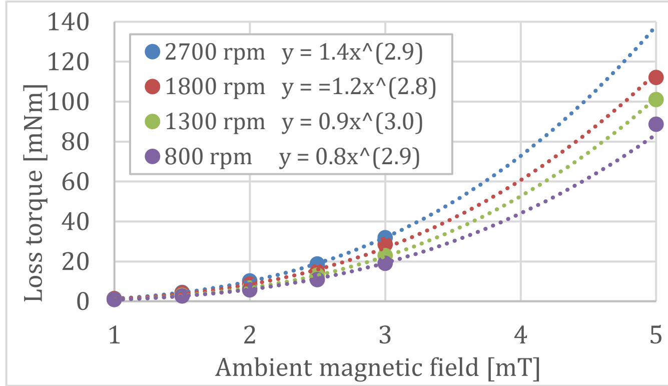


Figure 6 - Left: Test configuration (reaction wheel spin axis orthogonal to the magnetic field vector) Right: Loss torque vs. ambient magnetic flux density

For measuring the influence of ambient magnetic fields on wheel performance, the reaction wheel's loss torque was measured while generating magnetic fields with varying magnitude (following a specific waveform to ensure that the observed losses are evidently due to the external magnetic field). The test was repeated for magnetic flux densities ranging from 1.0 to 5.0 mT as well as with different reaction wheel orientations, i.e., spin axis parallel and orthogonal to the magnetic field vector. No measurable effect was observed when the field direction was parallel to the wheel spin axis. When the field was applied in a direction orthogonal to the spin axis, a significant change of the loss torque was identified, which closely followed the waveform of the external field vs. time.

Figure 6 (right side) shows the dependency of the measured loss torque vs. the magnitude of the ambient magnetic field. It can be seen that eddy current related loss torques can rise to levels of >100 mNm, i.e. nearly half the available motor torque. This happened, however, only for a very significant magnetic field of 5 mT, a level which is unlikely to occur in a real flight situation.

Moreover, it can be noted that there has been a cubic relationship between loss torque and flux density. This has been a surprising result since, according to Eq. 1, a square relationship would be expected. It is assumed that the geometry of the flywheel as well as the spatial distribution and direction of the external magnetic field play a critical role in the generated eddy current effects, which is subject to confirmation by ongoing research.

Conclusions

Eddy current related loss torque effects have been studied in depth, both in terms of simulation and hardware test results. A nonlinear dependency of the loss torque on relative motion speed has been confirmed, which can be coherently explained by the combined effect of a counteracting magnetic field (generated by the eddy currents) and a decrease of electrical conductivity due to the rise in temperature by Joule heating.

The results obtained and the consistency between simulation output and measurements are promising and give confidence in the fidelity of the analysis tools, particularly when mechanical, thermal and electromagnetic aspects are combined. Ongoing ESA research on the various loss torque components in reaction wheel assemblies and other space mechanisms will definitely benefit from the investigation. It will allow a more accurate prediction of mechanism performance (especially at higher speeds), for example in the frame of long-term health monitoring as outlined in [1].

Acknowledgments

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