MAGNETIC BRAKE FOR DRIVING UNITS FOR APPLICATIONS IN SPACE ENVIRONMENTS

Gregor Puchhammer [(1)], Hubert Mitterhofer [(2)], Karlo Radman [(2)], Roland Holzbauer [(3)], Marc Schuster [(3)], Asier Martinez [(4)]

[(1)] IIES – Inspired Innovation Engineering Services e.U., Lechthalergasse 49/30, 1230 Vienna, AUSTRIA,
Email: gregor.puchhammer@iies.eu
[(2)] LCM - Linz Center of Mechatronics GmbH, Altenberger Straße 69, 4040 Linz, AUSTRIA,
Email: Hubert.Mitterhofer@lcm.at
[(3)] AAC - Aerospace & Advanced Composites GmbH, Viktor-Kaplan Straße 2, 2700 Wiener Neustadt, AUSTRIA,
Email: roland.holzbauer@aac-research.at
[(4)] ESTEC, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, THE NETHERLANDS,
Email: Asier.Martinez.Carou@esa.int

ABSTRACT

Rotary actuators are commonly used on telecom satellite mechanisms for deploying and positioning large appendages. Unpowered holding torque and minimal energy consumption have become some of the most critical requirements for rotary actuator design and selection.

A novel working principle for magnetic brakes (MB) can realize both, the unpowered holding torque and minimal energy consumption demands. The reluctance torque generation corresponds to the unpowered stepper braking torque but with a much higher torque density. A short current pulse applied on a control coil toggles the brake state. Energy is only required for few milliseconds of the switching process itself, i.e. for locking or unlocking. In this paper, the terms locking / closing of the brake and unlocking / opening of the brake are used as equivalents. The MB provides a high number of stable braking positions for use with conventional stepper motors or with lighter BLDC motors without intrinsic unpowered braking torque. It has no tribological layer and operates without risk of debris generation.

REQUIREMENTS AND APPLICATIONS

The MB2-Rx magnetic brake (MB) is designed to support a wide range of driving applications on satellite platforms in space. A special design goal was the focus on robustness, compactness, long lifetime, and minimal energy consumption, while being highly adaptable to customer needs. Conventional rotary driving actuators without additional brakes make use of the detent torque capability of stepper motors. This may unnecessarily push the actuator size, weight and energy consumption of the motor due to the bad relation between unpowered detent and maximum powered torque.

The magnetic brake MB2-Rx will be a new off-the-shelf component which can be connected to either side of the motor or to an intermediate gear stage. The MB provides a high number of stable braking positions and high angular stiffness, and can be combined with conventional stepper motors (e.g. the SAGEM 21PP). It can also be used with lighter BLDC motors, as the motor does not need to provide any detent torque if coupled with the brake. The currently developed magnetic brake provides unique features, tailored for applications in space actuator systems:

- Holding torque of 80 – 200 mNm though contact-free working principle for maximum lifetime
- Powerless open and locked states, minimum energy for toggling the brake state.
- Number of stable brake positions per rotation: 200
- Applicable to any motor type with or without detent torque (BLDC, Stepper)
- No risk of wear and debris generation
- Overload rotation overriding the locked state does not damage the brake.
- Directly mounted on the customer shaft (no extra bearings needed)
- Drive direction: forward and reverse rotation (endless rotation) possible
- Only simple control electronics necessary
- Speed range 0 to 5000 rev / min, higher speeds possible

RELUCTANCE BRAKE

The brake is based on exerted torque due to a variable reluctance path along the rotational axis. Figure 1. Shows a topology using an inner rotor disc and outer stator ring with a variable airgap. A magnetic flux is closing over the stator and rotor parts, as shown in the simplified Figure 2. When the stator and rotor teeth are aligned, the system is in the position of minimal energy, and for any applied rotational load below the peak braking torque, the system will resist the angular position change. The peak braking torque is achieved at a quarter of the tooth-step, or 90° electrical angle, relative to 360° electrical angle

being the rotation from one aligned position to the next. The same effect is present in motor topologies with toothed airgap surfaces and permanent magnetic excitation, like the unpowered holding torque in stepper motors. This reluctance torque due to the passive magnetic flux must be overcome by the generated torque to rotate the stepper motor. Likewise, by applying a constant current, this static magnetic flux can be increased, which is known as the powered holding torque in stepper drives.
This novel magnetic brake is developed to provide a switchable braking torque without the need for the motor to overcome any unpowered braking torque as in state of art solutions [1]. Additionally, in contrast to non-contact hysteresis brakes, the reluctance brake has a torque independent of the rotational speed which is also exerted at standstill.

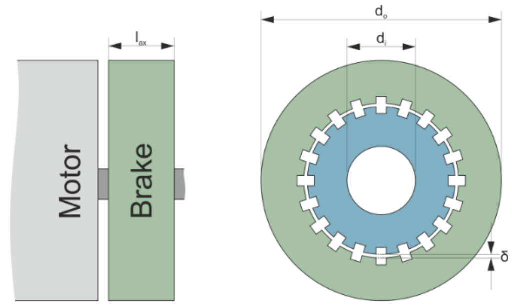

Figure 1: An example of the magnetic brake topology with 20 teeth and therefore 20 stable positions.

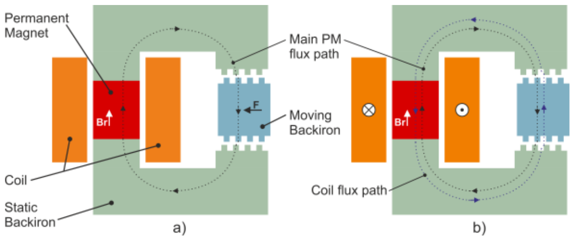

Figure 2: Simplified linear depiction of a basic reluctance magnetic circuit. a) Locked state. b) Unlocked state through active coil current .

The magnetic brake requirements include the open and closed state of the brake being unpowered. Thus, the holding torque must be generated by the passive magnetic flux. To open the brake, the magnetic flux in the airgap must be reduced to zero. This can be achieved by applying a current to a coil which generates a field opposing the permanent magnetic field, as seen in Figure 2. The drawback lies in the constant current needed while the brake is kept open. By permanently toggling the magnetic state of the brake, this constant power consumption can be avoided.

Principle of Operation

To operate the brake short current impulses are needed in the brake coil. The simplest control circuit is a full bridge connected to the DC power supply. Due to the inductance of the coil the current inrush will be delayed. As soon as the target current is reached, the brake state will be toggled. The brake will not switch from one state to the other by means of rotating the rotor or by temperature changes within the operating range.

The current impulse is required to be above a certain threshold to guarantee state switching at the worst operating temperature conditions. As the coil resistance is known, only the minimal voltage needs to be specified to guarantee a current above the threshold. No current control is required and a higher pulse peak or longer pulse duration do not influence the brake performance.

The operating principle can be separated in the following steps:

I. Unpowered closed brake. Stable position
II. Brake opening. Energy input during switching of brake state ~100ms.
III. Unpowered open brake. Stable position
IV. Brake closing. Energy input during switching of brake state ~100ms.

MECHANICAL ASSEMBLY AND CONSTRUCTION

The breadboard model MB2R3 (BB) was designed to fulfil the ESA defined requirements. The outer diameter of the BB is 55mm, the axial length is only 15mm.
In order to achieve a low total mass, a brake with a bearing-less design (as seen in Figure 4) was chosen. The MB consists of a rotor and a stator assembly. The stator of the MB has a ring shape with outer sided grooves for gluing purposes. Two fully redundant copper coils are part of the stator assembly. The control electronics and the coils are connected via separate, redundant wiring of each coil. Due to a simple coil arrangement,no internal cable connections are necessary, avoiding soldering or welding points.
Due to the working principle, only a small amount of energy is needed to toggle the states of the MB. Therefore, no extra cooling of the MB is required.
The rotor assembly consists of a threaded fastener to fix the rotor components together onto the shaft. An additional angular alignment device (AAD) for orienting the rotor on the shaft can be placed additionally on any side of the MB.

SYSTEM INTEGRATION

During the development, special attention was paid to the new brake concept and the simple integrability of the MB into any kind of rotary actuator drives. These considerations included consideration of mechanical, electrical, and thermal aspects.

Mechanical Integration

The design allows the MB to be mounted on the target (motor) shaft, so that the customer can tailor the bearing size for its own application. This feature saves a lot of unnecessary weight due to the absence of a doubled bearing system and of corresponding shaft couplings. The MB can be connected to either side of the motor or to an intermediate gear stage. In case the brake is connected to a stepper motor, special care must be taken to synchronize the torque ripple phase of the stepper with the stable positions of the brake. The best braking performance can be achieved by synchronizing the phases of the motor and the brake with each other. The angular alignment unit AAD (Figure 3b) is a specially created device for that task. It can be added on either side of the brake and connects the brake output and the shaft in a defined, angularly adjustable position. The angular alignment process is done using an Allen wrenchto turn the two opposing alignment bodies (yellow). If both alignment bodies are rotated four revolutions around their own axis of rotation, the angle between the shaft and the brake changes by 1.8 degree, which corresponds to a 360° phase shift variation between brake and motor. After the adjustment has been done, the device is firmly fixed with the MB output shaft using the threaded fastener.
The supply cablesof the MB can be aligned both, radially (as seen in Figure 3b) or axially, depending on the needs of the application.

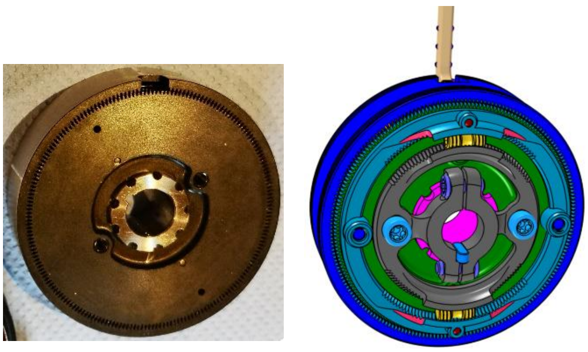

Figure 3: Breadboard model of the magnetic brake MB2R3 a) Physical model without AAD, b)BB design with AAD and radial supply cable orientation

Electrical Integration

The intended use of the magnetic brake on telecom satellites makes it necessary to adapt the electrical properties of the MB to the existing board electricity. A voltage terminal of 22 to 28 Volts has been specified by ESA. The satellite itself faces temperatures in the earth orbit between -40°C and 90°C. Hence, the coils are adapted to a maximum operating temperature of 100°C and the available minimum voltage of 22 Volts – respecting an additional 20°C self-heating tolerance. A rudimentary electronic circuit is necessary to operate the brake. A conventional H-bridge is sufficient to energize the coils for switching from the locked into the released state and vice versa.

Thermal Integration

Thermal considerations regarding the brake overheating were of lesser interest. Due to the fact that energy input is only needed during the switching of states, happening in ~100ms, the generated Ohmic loses in the coils are manageable by conduction towards the stator housing. Thermal constraints may arise in a use case with very frequent switching, i.e. an ongoing operation requiring a state switch every couple of seconds.

PROOF OF CONCEPT MEASUREMENTS

To test the performance of the magnetic brake in thermal vacuum, a test box with bearings to take up the stator and rotor has been designed and built. Figure 4 and Figure 5 show the breadboard measurement assembly. Rotor and stator of the brake are on top of the test box, the bearings and torque sensor are located on the bottom of the test box. The shaft is driven by a motor outside of the vacuum chamber and the temperature can be varied within a thermal shroud around the setup. The test box is mounted in a vacuum chamber with several feedthroughs for the electric signals and the rotating shaft. The angle between stator and rotor, the torque of the test box, the voltage and current for activation of the break were recorded during the tests.
With this setup the breadboard has been tested in air at room temperature and in vacuum from -45°C up to +100°C with several variations of locking and unlocking parameters.

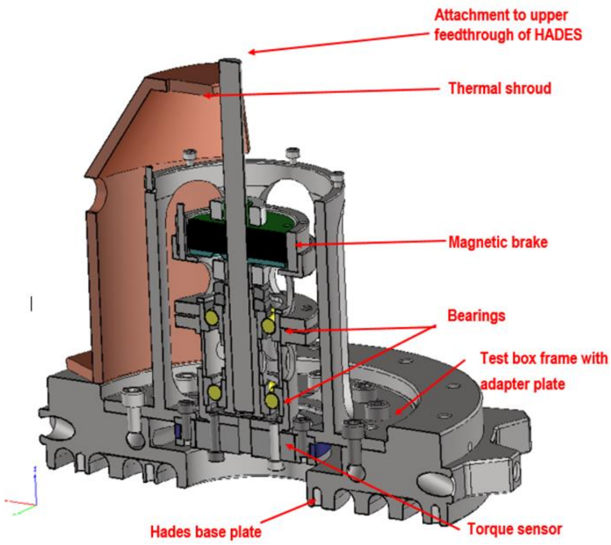

Figure 4: Breadboard TV-measurement assembly diagram

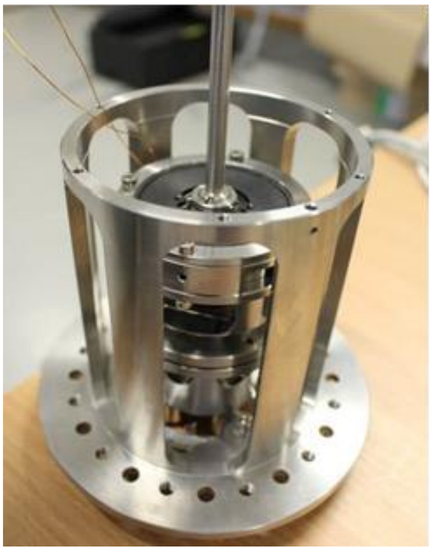

Figure 5: Breadboard measurement assembly by AAC

The measurements proved that the targeted performances are fulfilled:

- The magnetic brake clearly shows 200 identical stable positions.
- With an electric pulse of 20V, 6A and >26ms, the brake's state can be toggled.
- Lower power input might lead to residual holding torque in released state or reduced holding torque in locked state. – see Figure 6 and Figure 7. A current reduction to 4A will still achieve the full locking performance but leads to higher unlocked residual torques.
- The brake has a minimum holding torque of 133mNm (average of 149mNm) in all tested environments (vacuum from -45°C up to +100°C and ambient pressure room temperature)
- No degradation of performance in terms of holding torque / electric power for actuation was found.
- The brake has an average residual torque in unlocked mode of less than 0.4mNm – in case of nominal unlocking parameters.

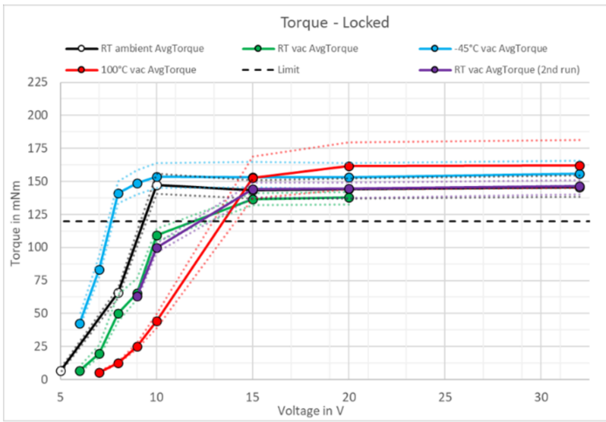

Figure 6: Measured brake performance in different environments. Above a supply voltage of 15V used for the ~100ms pulse, the brake state was fully toggled.

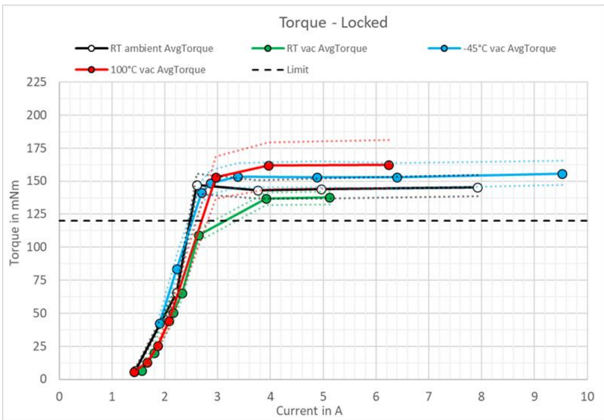

Figure 7: Measured brake performance in different environments. Plotted over the steady state current during the switching pulse.

PRELIMINARY BRAKE DATA

The breadboard model MB2R3 of the brake have shown the functionality of the new concept. Most of the requirements were met already at BB level. The required mean torque of 120mNm have been exceeded at all temperatures and also in vacuum (as can be seen in Table 1). Only the weight exceeds the target by 37% .

Table 1: Comparison of LCM Ansys simulation and AAC measurement results

Temperature	Torque acc. to requirement	Torque acc. to Simulation	Average torque measured (20V)
-45°C	120mNm	157mNm (-40°C)	153mNm (-9/+11)
Room temperature	120mNm	153mNm	144mNm (-7/+8)
Room temperature vacuum	120mNm	153mNm	138mNm (-5/+4)
+100°C	120mNm	153mNm	161mNm (-18/+18)

The new design adaptions for the engineering model MB2R5 focus on improvements for:

- Weight reduction: the requirements of 150 grams shall be met
- Current reduction: an adapted coil will be used, better suited for the satellite board net
- The outer diameter is reduced for better fit with existing stepper motors
- The axial length is reduced
- The torque density of the device is improved by more than 21%

These data are shown in Table 2 and reflect the refinements foreseen for the engineering model, which will be built in Q4/2021.

Table 2: Brake dimensions and power supply

	Requirement	BB	EM
Model		MB2R3	MB2R5
Outer Diam. [mm]	< 55.0	55.0	51.0
Inner Diam. [mm]	< 35.0	10.0	10.0
Axial Length [mm]	< 15.0	15.0	13.0
Weight [grams]	< 150.0	206.0	149.0
Braking torque [mNm]	80 - 200	153	120
Voltage [V]	22 - 28	15	20
Minimum Current [A]	-	4.0	-
Torque density [Nm/kg]		0.787	0.859

CONCLUSION

A new magnetic principle for a magnetic brake has been developed, manufactured and tested in relevant environment and temperatures. The concept of a switchable magnetic reluctance brake was evaluated in a BB, proving the full functionality and the high performance. The device weights 150 grams and is easy to integrate in new or existing rotary driving units. The magnetic brake can be used with conventional stepper motors or detent torque free BLDC motors. The phase synchronization of brake and motor is achieved by means of an angular alignment device. A simple switch is sufficient to control the brake. Debris and maintenance free operation guarantee long life capability.

REFERENCES

[1] CDA InterCorp, *"Stepper Motor Engineering Reference Data"*, 2000, www.cda-intercorp.com